Design study of beam transport lines for BioLEIR facility at CERN

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Design study of beam transport lines for BioLEIR facility at CERN

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ABSTRACT: The biomedical community has asked CERN to investigate the possibility to transform the Low Energy Ion Ring (LEIR) accelerator into a multidisciplinary, biomedical research facility (BioLEIR) that could provide ample, high-quality beams of a range of light ions suitable for clinically oriented, fundamental research on cell cultures and for radiation instrumentation development. The present LEIR machine uses fast beam extraction to the next accelerator in the chain, eventually leading to the Large Hadron Collider (LHC). To provide beam for a biomedical research facility, a new slow extraction system must be installed. Two horizontal and one vertical experimental beamlines were designed for transporting the extracted beam to three experimental end-stations. The vertical beamline (pencil beam) was designed for a maximum energy of 75 MeV/u for low-energy radiobiological research, while the two horizontal beamlines could deliver up to 440 MeV/u. One horizontal beamline shall be used preferentially for biomedical experiments and shall provide pencil beam and a homogeneous broad beam, covering an area of $5 \times 5\,cm^2$ with a beam homogeneity of $\pm 5\%$. The second horizontal beamline will have pencil beam only and is intended for hardware developments in the fields of (micro-)dosimetry and detector development. The minimum full aperture of the beamlines is approximately 100 mm at all magnetic elements, to accommodate the expected beam envelopes. Seven dipoles and twenty quadrupoles are needed for a total of 65 m of beamlines to provide the specified beams. In this paper we present the optical design for the three beamlines.

KEYWORDS: Accelerator Applications; Beam dynamics; Beam Optics

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Contents

1   BioLEIR: a proposed biomedical research facility hosted at CERN

Cancer is a critical societal issue. Worldwide, over 32 million people live with cancer, mostly untreated [1]. Radiation therapy is an essential component of effective cancer control. In Europe, about half of the number of patients diagnosed with cancer are treated with radiation therapy and every other cured patient undergoes radiation therapy as part of their treatment. The main aim of radiation therapy is to deliver a maximally effective dose of radiation to a designated tumour site while sparing the surrounding healthy tissues as much as possible.

The use of ion beams in tumour treatment was first proposed more than 60 years ago, when the depth-dose characteristics of proton beams were investigated by Wilson [2]. Since then, ion beam therapy has evolved and significantly expanded. The use of proton therapy as an alternative to conventional radiation (i.e. photons and electrons) has led to important developments and refinements in conventional treatment techniques. A comparison of depth-dose curves for photon, proton, and carbon ion beams is shown in figure 1. It can be seen that the dose decreases exponentially with penetrating depth for conventional radiation (photons). However, charged particles deposit almost their full energy at an energy-dependent material depth, resulting in the so-called Bragg peak. This characteristic energy deposition allows for highly conformal treatment of deep-seated tumours with great accuracy, while delivering minimal doses to healthy surrounding tissue [3].

The last two decades have seen a dramatic rise in the number of particle therapy centres coming online and promising results have been observed. Still, the achieved advantages in this field are felt to be preliminary, based on scattered physical and biological studies, spread over many years, and performed in different centres under heterogeneous conditions, resulting in significant systematic uncertainties. There is also criticism on the lack of large-scale clinical or preclinical studies data to support assumptions on the effectiveness of hadrontherapy.

Consequently, to fully utilize the benefits of particle therapy, a concerted research effort is required to provide the biological and physical data sets and innovative diagnostics and treatment tools to help derive the optimal use of this advanced therapy.
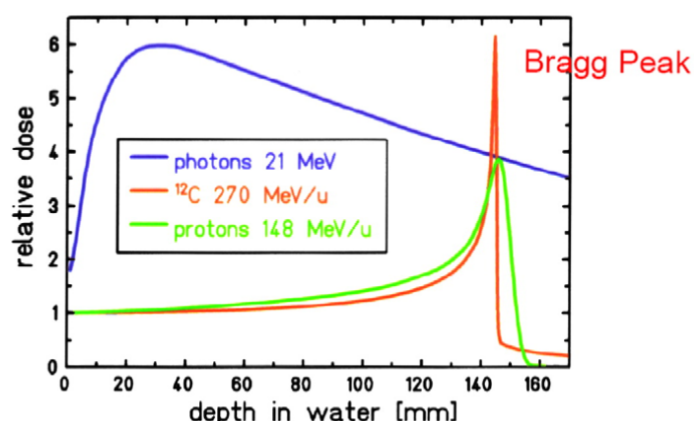
Figure 1. Depth-dose profiles for photons, protons, and carbon ions. It can be seen that a large part of the energy of protons and carbon ions is liberated in a very narrow peak known as the Bragg peak [4].

A dedicated centre for fundamental, biomedical research, offering extended blocks of beam time, with a variety of ions and energies provided, is urgently needed, as the existing hadrontherapy centres do not have sufficient beam time available for the non-clinical research efforts needed.

The need for an open-access biomedical facility dedicated to medically-oriented, fundamental research for optimising hadrontherapy was first raised at the European Network for Light Ion Hadron Therapy (ENLIGHT) meeting in Oropa, Italy in 2005 [5] and later at the 2010 Physics for Health workshop [6], where members of the biomedical and physics community jointly asked CERN to take the lead on this initiative. In 2012, a brainstorming meeting suggested the possibility of modifying the existing Low Energy Ion Ring (LEIR) accelerator to establish BioLEIR [7].

The aim of BioLEIR is to provide a unique facility with a range of ion beams and energies suitable for multidisciplinary, medical-physics-oriented research. The facility would be capable of providing a range of different fully stripped ion species (e.g. protons, He, Li, Be, B, C, N, O) [8].

2 Beam transport lines to the BioLEIR experimental area

The LEIR accelerator at the BioLEIR facility is envisioned to provide beams for a range of light ions from protons up to at least Oxygen for the purposes of biomedical research. The experimental irradiation area of BioLEIR is planned to be in the "South Hall" area adjacent to the LEIR accelerator at CERN.

Three irradiation rooms are envisioned at the BioLEIR facility. These rooms are planned to be operationally independent of each other, with independent access and respective dedicated purpose and applications. Each of the three irradiation rooms has its specific constraints in terms of maximum particle energy and beam intensity:

- Horizontal beamline, H1: intended for biomedical experiments on cells, with ion energies up to 440 MeV/u and intensities between 10^8 and 10^{10} protons/s on target, as well as 10^8 to 10^9 ions/s on target for light ions. A pencil beam of 5–10 mm FWHM (Full Width Half Maximum), including a beam deflection system for scanning, as well as a homogeneous broad beam of 5×5 cm^2, are available at this irradiation point.

- Horizontal beamline, H2: reserved for phantom work, (micro-)dosimetry and detector development, with ion energies up to 440 MeV/u and intensities up to 10^{10} protons/s on target, and up to 10^9 ions/s on target for light ions. A pencil beam of 5–10 mm FWHM with a scanning system is available at this irradiation point.

- Vertical beamline, V: intended for specific low-energy radiobiological research, with ion energies up to 75 MeV/u and ion intensities up to 10^8 ions/s on target. The vertical irradiation room shall receive a pencil beam of 5–10 mm FWHM. There will be no scanning system in order to achieve an endpoint for the vertical beamline that remains below the constraint from the overhead crane (7.95 m), see figure 2. In the vertical irradiation room, scanning will be achieved by moving the sample around the isocenter with a motorized sample holder table, rather than deflecting the beam.

The physical beam parameters of the BioLEIR facility are planned to be as similar as possible to the achievable beam parameters as implemented in already existing clinical synchrotron facilities based on the Proton-Ion Medical Machine Study (PIMMS) [9]: HIT [10], CNAO [11] and MedAustron [12]. This shall facilitate collaboration and exchange of data between all facilities providing beam for non-clinical biomedical research. Table 1 summarizes the beam parameters with which the BioLEIR facility is planned to operate.

Table 1. Summary of the operational beam parameters for the BioLEIR facility.

Ion species		proton	Helium to Argon
Energies	Horizontal:	50-250	50-440
[MeV/u]	Vertical:	<70	<70
Intensities			
[ions/s on target]	Horizontal:	10^8-10^{10}	10^8-10^9
	Vertical:	10^8	10^8

The layout of the three experimental beamlines (i.e. two horizontal and one vertical) is shown schematically in figure 2. The common horizontal beamline has a 132° bending angle, accomplished with three identical dipoles (beam rigidity $B\rho$ = 6.7 T.m), with a quadrupole triplet between the second and third dipoles, and an additional dipole further downstream for each beamline. The fourth dipole in the H1 beamline is reversed. The vertical beamline has a 90° bend ($B\rho$ = 2.6 T.m), using a split 45° dipole pair with an interposed quadrupole, as shown in figure 3. For the vertical beamline, a single quadrupole is used to make the bend achromatic, while for the horizontal beamlines a quadrupole triplet is used between the second and third dipoles in the common part of the beamline to cancel the horizontal dispersion coming from the LEIR ring. A further set of quadrupole magnets in each beamline is needed to allow (de-)focusing of the beam onto the target plane.

The third and fourth dipoles in the common beamline are equipped with 'Y' chambers to enable switching between the different experimental stations. The beamline minimum full aperture is approximately 100 mm at all magnetic elements, to accommodate the expected beam envelopes. Seven dipoles and twenty quadrupoles are needed for a total of 65 m of beamlines to provide the specified beams shown in table 1.
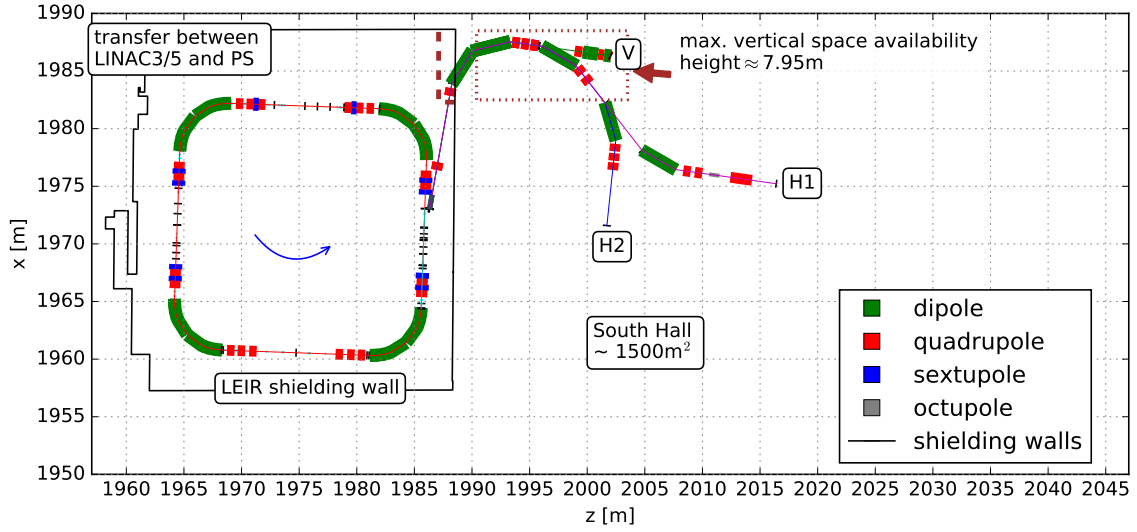
Figure 2. Layout of LEIR and experimental beamlines. A possible layout for two horizontal beamlines is shown, with a vertical beamline branching from the common horizontal line before the third dipole in the common beamline. The brown dashed line shows the modification of the LEIR shielding wall to allow the extraction line to cross over to the South Hall, while the brown dotted line shows the delineations where the maximum vertical space is available.
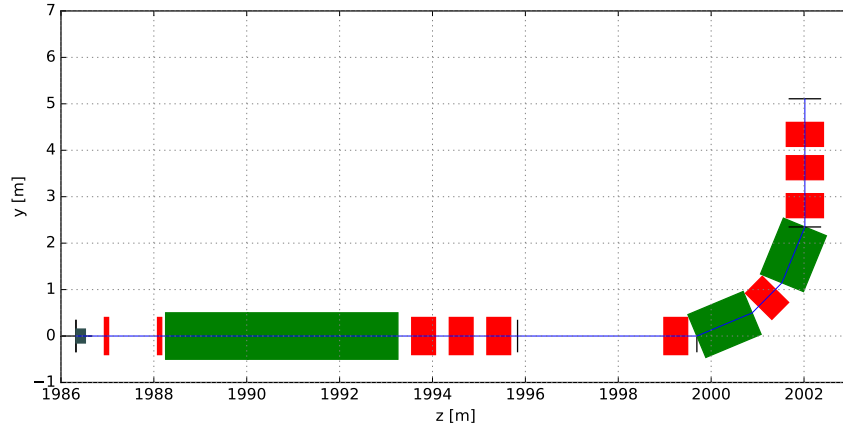
Figure 3. Survey plot of the vertical beamline in z-y plane. The vertical target plane is located about 6.5 m above the LEIR floor level.

The extracted beam from the LEIR ring [13] is assumed to travel through the LEIR kicker tank (KFH3234 element) at x = -42 cm and x' = -140 mrad [14] so that a first quadrupole magnet $qc1$ can be placed 3.5 m downstream of the entry to the kicker tank. The drift space between quadrupole magnets $qc1$ and $qc2$ is planned to be 6.02 m in order to allow enough space for the modified LEIR shielding wall between the two quadrupole magnets, as shown in figure 2. The proposed layout permits installation of the vertical beamline at the location of maximum available vertical space while respecting existing building walls. This layout is building on earlier work done by Abler et al. [14].

The decision to dump the beam may be taken at almost any time. In such a case, no beam shall reach any of the BioLEIR irradiation areas. In order to safely dispose of the beam during setting up or as an emergency measure during operation, the fast extraction system in the LEIR ring should be activated, on top of the slow extraction, to extract the beam in less than one turn towards the fast extraction channel where a dump is pre-inserted. As the three irradiation rooms are planned to be independently accessible, each beamline is protected by two elements: one beam stopper and one bending magnet.

3 Beam transport lines design

Optically, the transport and matching are constrained by the space available in the South Hall, the optics functions and beam sizes at the LEIR extraction point, the matching of the dispersion and its derivative to zero at the target, and by the required beam sizes and uniformity at the target planes. The initial conditions at the first electrostatic extraction septum in the LEIR ring and at the target planes at the beamline extremities are given in table 2.

The vertical beamline is designed for a maximum energy of 75 MeV/u (beam rigidity $B\rho$ = 2.6 T.m), while the horizontal beamlines should deliver up to 440 MeV/u ($B\rho$ = 6.7 T.m). All energies are kinetic, and quoted for $^{12}C^{6+}$. The MAD-X (Methodical Accelerator Design computer program, version X [15]) software suite was used for beam optics studies and beamline matching.

Table 2. Initial and final conditions for beamline matching.

	ϵ_{rms} [π.mm.mrad]	β [m]	D [m]	D'	α
Initial parameters at first electrostatic septum					
Vertical	0.6–4.2	15	0	0	−2.8
Horizontal	2	15	−4	−1	0
Target parameters at end of beamlines					
Pencil	–	1	0	0	0
Broad	–	50	0	0	0

3.1 Dipole and quadrupole magnets

The beam transport lines were designed using 'sector' bends, where the beam enters the dipole perpendicular to the pole face. The gap field is 1.5 T for both the vertical and horizontal dipoles. The resulting horizontal beamline dipoles are 3.415 m (magnetic) along the curved beam trajectory and the vertical beamline dipoles are 1.335 m. The dipoles shall be laminated and curved to follow the beam trajectory, such as to significantly reduce the horizontal aperture required and the magnet size. The main dipole parameters are given in table 3.

The quadrupole magnets are assumed to be 0.517 m long, with a nominal gradient of around 25 Tm^{-1}. The actual strengths in operation vary considerably depending on the optics and on the beamline. A total of 20 installed quadrupole magnets are needed for the three beam transport lines. The main quadrupole parameters are given in table 4.

Table 3. Extraction beamlines main dipole parameters.

Extraction beamline dipoles	Unit	H-dipole	V-dipole
Max beam rigidity	T.m	6.7	2.6
Dipole bend angle	deg	44	45
Gap dipole field	T	1.5	1.5
Magnetic length	m	3.415	1.335
Integrated field	T.m	5.1	2.0
Number installed (spare)		5 (1)	2 (1)

Table 4. Extraction beamlines main quadrupole parameters.

Extraction beamline quadrupoles	Unit	Value
Max beam rigidity	T.m	6.7
Magnetic length	m	0.517
Nominal gradient	$T.m^{-1}$	25
Integrated gradient	T	13
Normalised gradient	m^{-2}	3.8
Integrated normalised gradient	m^{-1}	2.0
Inscribed pole tip radius	mm	50
Nominal pole tip field	T	1.25
Number installed (spare)		20 (2)

## 3.2 Optics functions and beam envelopes

Detailed optics calculations have been made for all three beamlines. The horizontal beamline H1 allows for the optics functions in the target plane to be adjusted over a range of $\beta = 1 - 50$ m, as illustrated in figures 4 and 5. We conclude that it will fulfill field size and homogeneity criteria (broad beam uniformity better than 90%). Enforcement of achromatic beam transfer through the common horizontal bending segment defines the strengths of the initial quadrupoles, and the optical functions in this part of the line show little dependency on target parameters. The optics and envelope plots for the second horizontal beamline H2 and the vertical beamline V are shown in figures 6 and 7, respectively.

The maximum beam envelopes are kept within ±50 mm (see table 5) by keeping the beta functions below 100 m. This was achieved via optimisation of the quadrupoles locations and strengths.

4 Discussion

It shall be noted that the beam half-widths shown in figures 4–7 are calculated using 2.5 σ envelopes for the rms emittances and assuming a maximum momentum spread of $\delta p/p = 0.2\%$ throughout the line. No effects from mechanical inaccuracies, alignment errors nor trajectory excursions are included, which means that the realistic aperture for the beamline is likely to be closer to 2σ. This does not represent a particular issue for the intensity delivered to the targets, but needs to be investigated in terms of beam loss and activation, and in terms of collimation and beam purity at the targets.
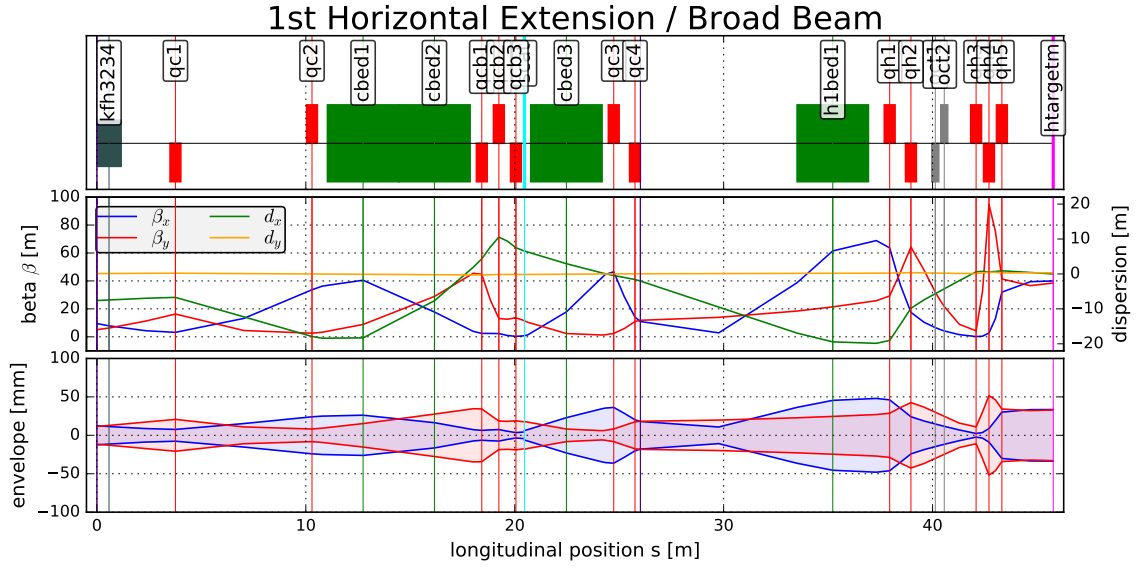
Figure 4. Optics and beam envelope plots for horizontal line H1, for broad beam optics with $\beta = 50\,\mathrm{m}$ in the target plane.
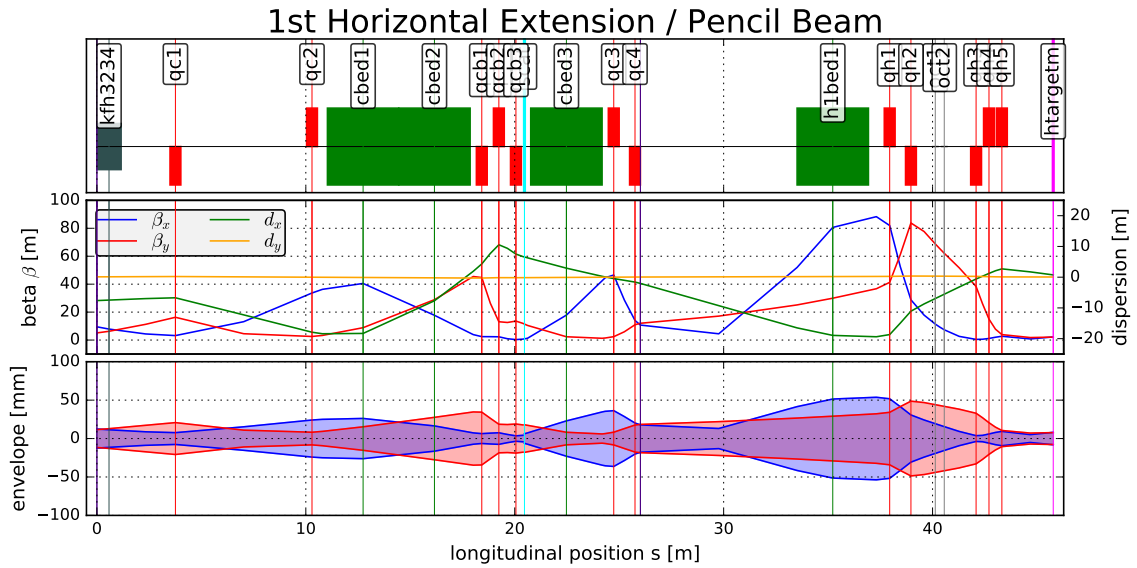
Figure 5. Optics and beam envelope plots for horizontal line H1, for pencil beam optics with $\beta = 1\,\mathrm{m}$ in the target plane.
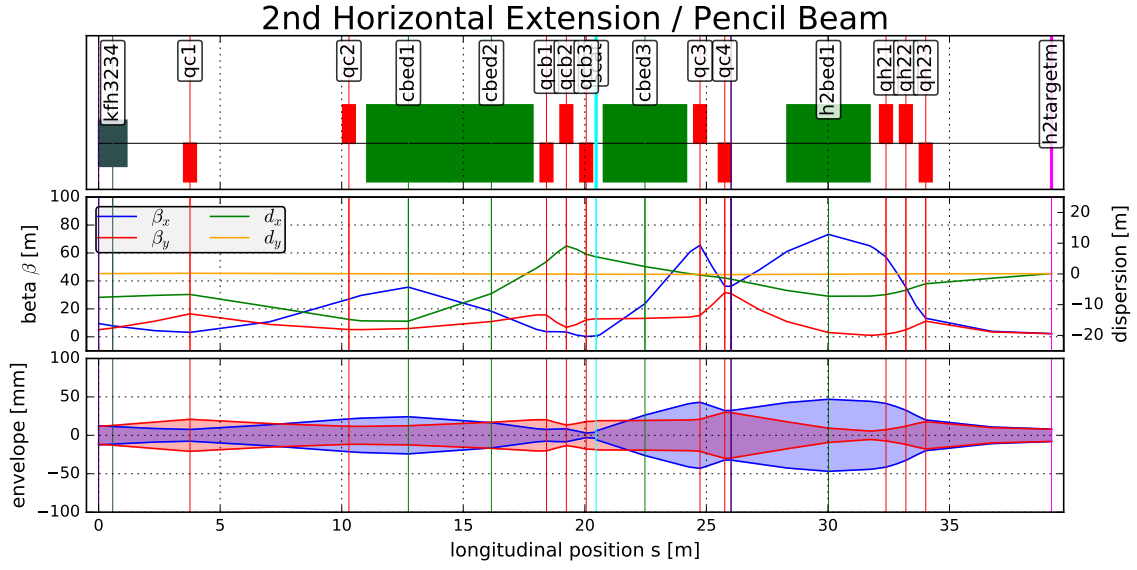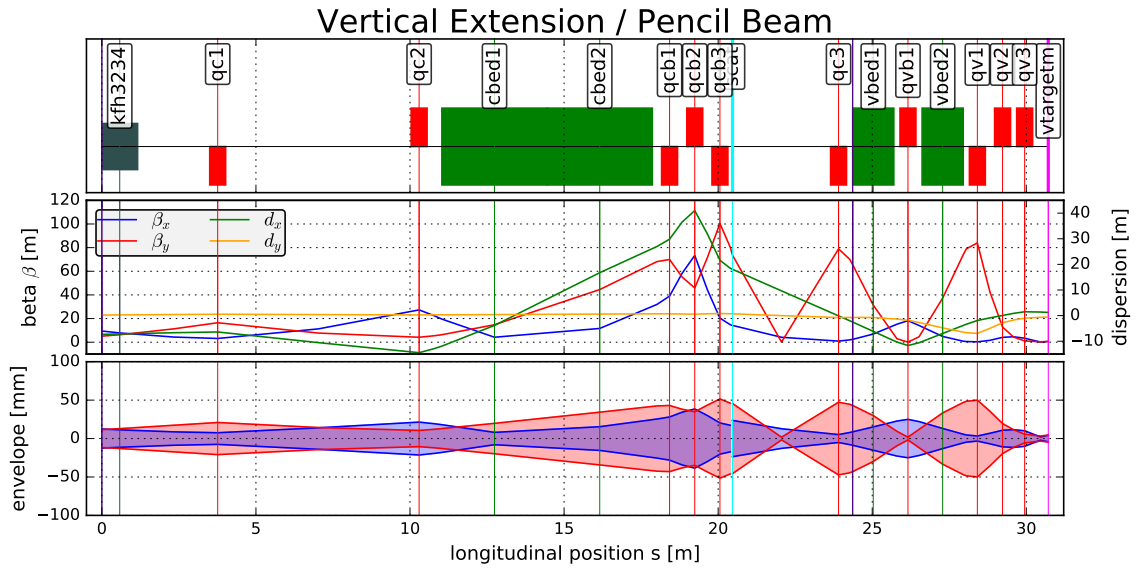
Figure 6. Optics and beam envelope plots for horizontal line H2, for pencil beam optics with $\beta = 1$ m in the target plane.

Figure 7. Optics and beam envelope plots for vertical line V, for pencil beam optics with $\beta = 1$ m in the target plane.

Table 5. Maximum quadrupole gradients (k) and beam envelopes (BE) for the common transport line and the two horizontal & one vertical extensions.

(a) Common beamline.

	qc1	qc2	qcb1	qcb2	qcb3	qc3	qc4
k [T/m]	−3.9	1.8	−10.6	18.0	−5.7	8.8	−7.6
BE [mm]	±22	±25	±35	±19	±19	±36	±20

(b) First horizontal extension H1.

	qh1	qh2	qh3	qh4	qh5
k [T/m]	6.8	−8.9	36.8	−39.3	18.9
BE [mm]	±50	±49	±34	±50	±35

(c) Second horizontal extension H2.

	qh21	qh22	qh23
k [T/m]	2.3	2.6	−8.8
BE [mm]	±41	±33	±20

(d) Vertical extension V.

	qvb1	qv1	qv2	qv3
k [T/m]	4.6	−6.2	6.2	9.6
BE [mm]	±30	±49	±20	±12

All main dipoles are envisaged to be powered individually as it is an advantage for trajectory correction. It is assumed that there are 5 horizontal dipole converters and 2 vertical dipole converters. A few of the quadrupole converters require to switch polarity between pencil and broad beam optics. Some optimisation may be possible for similar strength quadrupoles by rematching and powering in series, to reduce the number of power supplies.

Apart from the design of the beamline elements and their associated integration, the main unresolved technical issue appears to be the required uniformity at the target, which is strongly linked to the collimation and beam purity that can be expected.

A homogeneous broad beam can be obtained by strong beam defocusing and then collimating the defocused beam before the target, allowing only for the central portion of the beam to impinge on the target. This mechanism results in high beam loss and activation of the surrounding materials. An alternative option could be the use of a tail folding mechanism to achieve a uniform transverse distribution, requiring the addition of strong octupole magnets for the over-focusing, see e.g. [16]. This approach has been implemented successfully in the past and is expected to be applicable at BioLEIR. Tentatively, the octupoles would need a strength $\frac{\partial^3 B_y}{\partial x^3}$ of around $3 \times 10^4 \, \mathrm{Tm^{-3}}$ and be 0.33 m long. The tail folding mechanism would have the advantage of increasing the intensity on target, and hence reducing irradiation times. The tail folding approach needs further investigations for both, the achievable beam purity as well as the beam loss and activation aspects.

5 Conclusions

Two horizontal and one vertical experimental beamlines have been designed for the BioLEIR facility, to transport the extracted beam from the LEIR accelerator to the experimental end-stations, taken into consideration several constraints, from optics design to physical layout of the hall and optimization of shielding requirements. The vertical beamline was designed for a maximum energy of 75 MeV/u, while the horizontal beamlines should deliver up to 440 MeV/u. A pencil beam of 5–10 mm FWHM as well as a homogeneous broad beam of 50×50 mm^2 are available at the first horizontal (H1) irradiation point, while only a pencil beam of 5–10 mm FWHM is available at the second horizontal (H2) and vertical (V) irradiation points.

References

[1] J. Ferlay et al., *Cancer incidence and mortality patterns in Europe: Estimates for 40 countries in 2012*, *Eur. J. Cancer* **40** (2013) 1374.

[2] R. Wilson, *Radiological use of fast protons*, *Radiology* **47** (1946) 487.

[3] S. Ghithan, *Development of a PET cyclotron based irradiation setup for proton radiobiology*, Ph.D. Thesis, University of Coimbra, Portugal (2014), https://estudogeral.sib.uc.pt/bitstream/10316/26977/1/SharifGhithan_PhDthesis_EstudoGeral.pdf.

[4] E. Fokas, G. Kraft, H. An and R. Engenhart-Cabillic, *Ion beam radiobiology and cancer: Time to update ourselves*, *Biochim. Biophys. Acta* **1796** (2009) 216.

[5] *Fourth General Meeting of Enlight*, Oropa, Italy (2005), http://cerncourier.com/cws/article/cern/29442.

[6] *ICTR-PHE*, Geneva, Switzerland (2012), http://ictr-phe12.web.cern.ch/ICTR-PHE12.

[7] *Meeting — Possible Medical Facility at CERN*, Geneva, Switzerland (2012), https://indico.cern.ch/event/193910/.

[8] S. Ghithan, G. Roy and S. Schuh eds., *Feasibility Study for BioLEIR*, CERN, Geneva, *CERN Yellow Reports: Monographs* **1/2017** (2017) [CERN-2017-001-M],

[9] L. Badano et al., *Proton-Ion Medical Machine Study (PIMMS)*, CERN/PS 99–010 (DI), CERN, Geneva [*Technical Report* (2014)].

[10] *Heidelberg Ion-Beam Therapy Center (HIT)*, Germany, https://www.klinikum.uni-heidelberg.de/Welcome.113005.0.html?&L=1.

[11] *The National Centre of Oncological Hadrontherapy (CNAO)*, Italy, http://fondazionecnao.it/en/.

[12] *MedAustron Particle Accelerator*, Austria, http://www.medaustron.at/en/particle-accelerator.

[13] A. Garonna, D. Abler and C. Carli, *Proposal for a Slow Extraction System for a Biomedical Research Facility at CERN based on LEIR*, in *Proceedings of IPAC2014*, Dresden, Germany, MOPRI094 (2014).

[14] D. Abler, C. Carli, A. Garonna and K. Peach, *Study of beam transport lines for a biomedical research facility at CERN based on LEIR*, in *Proceedings of IPAC2014*, Dresden, Germany, MOPRI095 (2014).

[15] *MAD-X (Methodical Accelerator Design computer program, version X)*, http://mad.web.cern.ch/mad.

[16] Y.K. Batygin, A. Scheinker, S. Kurennoy and C. Li, *Suppression of Space Charge Induced Beam Halo in Nonlinear Focusing Channel*, *Nucl. Instrum. Meth.* **A 816** (2016) 78 [arXiv:1602.05107].