Formation of a uniform ion beam using octupole magnets for BioLEIR facility at CERN

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ABSTRACT: The possibility to transform the Low Energy Ion Ring (LEIR) accelerator at CERN into a multidisciplinary, biomedical research facility (BioLEIR) was investigated based on a request from the biomedical community. BioLEIR aims to provide a unique facility with a range of fully stripped ion beams (e.g. He, Li, Be, B, C, N, O) and energies suitable for multidisciplinary biomedical, clinically-oriented research. Two horizontal and one vertical beam transport lines have been designed for transporting the extracted beam from LEIR to three experimental end-stations. The vertical beamline was designed for a maximum energy of 75 MeV/u, while the two horizontal beamlines shall deliver up to a maximum energy of 440 MeV/u. A pencil beam of 4.3 mm FWHM (Full Width Half Maximum) as well as a homogeneous broad beam of 40×40 mm², with a beam homogeneity better than ±4%, are available at the first horizontal (H1) irradiation point, while only a pencil beam is available at the second horizontal (H2) and vertical (V) irradiation points. The H1 irradiation point shall be used to conduct systematic studies of the radiation effect from different ion species on cell-lines. The H1 beamline was designed to utilize two octupole magnets which transform the Gaussian beam distribution at the target location into an approximately uniformly distributed rectangular beam. In this paper, we report on the multi-particle tracking calculations performed using MAD-X software suite for the H1 beam optics to arrive at a homogeneous broad beam on target using nonlinear focusing techniques, and on those to create a Gaussian pencil beam on target by adjusting quadrupoles strengths and positions.

KEYWORDS: Accelerator Applications; Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Beam dynamics; Beam Optics

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1 BioLEIR facility

Advanced radiotherapy using proton, Carbon ion or other ion beams (hadrontherapy) to deliver a maximally effective dose of radiation to a designated tumour site, has gained huge momentum over the last two decades. Many new centres have been built, and many more are under construction. Compared with photon beam radiotherapy, hadrontherapy allows more selective deposition of radiation dose in various cancers while reducing dose to surrounding healthy tissues. Heavier ions (e.g. Carbon ions), in addition, due to the higher density of ionisation events along the particle track, exhibit a higher relative biological effectiveness than X-rays or protons, making them prime candidates for the treatment of also radio-resistant tumours. Still, these advantages are felt to be preliminary, based on scattered physical and biological studies, spread over many years, and performed in heterogeneous centres under different 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 hadron therapy [1].

Particle irradiation and the impact in vitro have been reported in a number of publications, resulting in a large range of Relative Biological Effectiveness (RBE) data from a number of different cell lines and endpoints. These studies have been very useful in confirming to a large extent the hypotheses of the effect of particle irradiation. Nevertheless, the heterogeneity between the different studies makes it hard to combine the obtained data and to draw definitive conclusions [1]. A dedicated centre for biomedical research, which is urgently needed, will not only provide the necessary beam time in large time blocks, but also will foster closer collaborations between research teams from different countries to rapidly move the field of hadron therapy forward. Such a dedicated centre will serve to optimise hadron therapy and help current and future hadron therapy centres worldwide, which shall contribute to further improving radiotherapy outcomes and potentially decreasing of mortality rates in cancer patients [1, 2]. The Low Energy Ion Ring (LEIR) accelerator at CERN shall provide a beam for a range of light ions from protons up to at least Oxygen for
the purposes of biomedical research [1]. The idea of modifying the existing LEIR accelerator to establish a biomedical research facility (BioLEIR) was suggested during a brainstorming meeting at CERN in 2012 [3]. The optics functions and properties of LEIR accelerator (i.e. duty cycle, ring lattice, families of correctors, and momentum acceptance, etc.) can be found in [1, 4, 5]. The proposed biomedical research facility at CERN (BioLEIR) has one horizontal (H1) and one vertical (V) irradiation points for biomedical research and a second horizontal (H2) irradiation point for research more related to (micro-)dosimetry development and fragmentation studies. The vertical beamline allows irradiation of cells in the growth medium where the cells can be kept in aqueous phase medium [1, 6]. The present LEIR uses only fast beam extraction to the next accelerator of the ion chain eventually leading to the Large Hadron Collider (LHC). To provide beam for a biomedical research facility, a new slow extraction needs to be installed [1]. A short transfer line brings the ions to two horizontal beamlines with energies up to 440 MeV/u (beam rigidity $B_\rho = 6.7$ T.m) for most light ions of interest. A vertical beamline with energies up to 75 MeV/u ($B_\rho = 2.6$ T.m) completes the facility. All energies are kinetic, and quoted for fully stripped Carbon ions $^{12}$C$^{6+}$ [6].

The experimental beamlines and end-stations are shown in figure 1. The first horizontal (H1) irradiation point is intended for biomedical experiments on cells, with ion energies between 50 MeV/u and 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 other light ions. A pencil beam of 4–10 mm FWHM as well as a homogeneous broad beam of $40 \times 40$ mm$^2$ are available at this irradiation point, while only a pencil beam is available at the second horizontal (H2) and vertical (V) irradiation points.

![Image](image_url)

Figure 1. Layout of LEIR accelerator 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 black 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. Two octupole magnets (33-cm-long each) can be seen in gray between the quadrupole doublet and triplet at the end of the H1 beamline.
2 Beam transport optics

The beam transport and matching are constrained by the space available in the South Hall (see figure 1), the optics functions and beam sizes at the LEIR extraction point in both planes (horizontal and vertical), the optics functions at the target positions in both planes, and by the required beam sizes and uniformity at the target planes. The initial conditions at the LEIR extraction point and at the target planes at the beamline extremities are given in table 1. Seven dipoles, twenty quadrupoles, and two octupoles are needed to provide the specified beams for the three beamlines. The main dipole, quadrupole, and octupole parameters are given in table 2.

Table 1. Initial and final conditions for the three beamlines matching at the BioLEIR facility. The Twiss parameter \(\alpha\) and the dispersion (D) and its derivative (D’) are matched to zero at the target in both planes [6].

| \(\varepsilon_{\text{rms,norm}} [\pi \text{mm.mrad}]\) | \(\beta \text{ [m]}\) | D [m] | D’ | \(\alpha\) |
|---|---|---|---|---|
| **Initial parameters at LEIR extraction point** | | | | |
| Vertical (V) | 0.6–4.2 | 15 | 0 | 0 -2.8 |
| Horizontal (H) | 2 | 15 | -4 | -1 | 0 |
| **Final parameters at the target planes** | | | | |
| Pencil (H & V) | — | 1 | 0 | 0 | 0 |
| Broad (H & V) | — | 40 | 0 | 0 | 0 |

Detailed optics calculations have been made for the first horizontal beamline H1, which allows for the optics functions in the target plane to be adjusted over a range of \(\beta = 1 \sim 40\) m, as illustrated in figures 2 and 3.

Figure 2. Optics and beam envelope plots for horizontal line H1, for pencil beam optics with \(\beta = 1\) m in the target plane.
Table 2. Main dipole, quadrupole, and octupole parameters for the three beamlines at BioLEIR.

(a) Transport 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)    |

(b) Transport beamlines main quadrupole parameters.

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

(c) Transport H1 beamline main octupole parameters.

| Extraction beamline octupoles  | Unit   | Value         |
|---------------------------------|--------|---------------|
| Max beam rigidity               | T.m    | 6.7           |
| Magnetic length                 | m      | 0.33          |
| Nominal strength                | T.m\(^{-3}\) | 3 \times 10^4 |
| Inscribed pole tip radius       | mm     | 50            |
| Nominal pole tip field          | T      | 3.75          |
| Number installed (spare)        |        | 2 (1)         |

All main dipoles are envisaged to be powered individually to allow for more variables for trajectory correction. It is assumed that there are 5 horizontal dipole converters (i.e. power converters) and 2 vertical dipole converters for the three beamlines.

3 Pencil beam

Figure 4 shows the two-dimensional density distribution of the 440 MeV/u fully stripped Carbon ions beam at the target position at the end of the H1 beamline, for the case when the two octupoles in the H1 beamline are not powered. It is observed that the beam distribution is Gaussian in both
planes with a FWHM of 4.3 mm (i.e. pencil beam). The whole target area can be irradiated using a scanning system. The beam profiles corresponding to the target front plane, a 10 cm depth in the target, and a 20 cm depth in the target are shown in figure 5. It is noted that the FWHM value of the Gaussian profiles in both planes increases slightly with target depth.

### 4 Uniform beam

A uniform broad beam can be obtained by strong beam defocusing and then collimating the defocused beam before the target, allowing only for the central portion (∼2%) of the Gaussian beam to impinge on the target. This mechanism results in high beam loss and activation of the surrounding materials. An alternative is the use of a tail folding mechanism to achieve a uniform transverse distribution, which requires the addition of octupole magnets. The tail folding mechanism has the advantage of increasing the intensity on target, hence reducing irradiation times and lower activation along beamline [7].

This method of generating uniform beam distributions at the target plane is based on magnetically focusing the transported beam by applying nonlinear forces. A beam distribution that is Gaussian in all transverse coordinates can be transformed into an approximately uniform profile in real coordinate space using octupole magnets, where the phase-space ellipse is distorted into an S-shape by the nonlinear force [8, 9].

The first horizontal beamline (H1) at the BioLEIR facility was designed to use two magnetic octupole elements (one for each plane) which transform the Gaussian beam distribution at the location of the target into a beam with rectangular cross section, and the beam is approximately uniformly distributed over the irradiated target. Figure 6 shows the two-dimensional distribution of the 440 MeV/u fully stripped Carbon ions beam at the target position at the end of the H1 beamline (broad beam). The beam is focused using two octupole magnets, where the octupoles strengths were optimized to achieve an approximately uniform transverse distribution (see table 3). It can
Figure 4. Two-dimensional density distribution of the 440 MeV/u fully stripped Carbon ions beam at the target plane at the end of the H1 beamline. The beam distribution is Gaussian in both planes with a FWHM of 4.3 mm.

It can be seen that the central portion of the beam spot is uniform in both planes (~20% of the beam), with a homogeneity of ±2% and ±4% in the x- and y-planes, respectively. The beam profiles corresponding to the target front plane, a 10 cm depth in the target, and a 20 cm depth in the target are shown in figure 7. It can be pointed out that the beam size does not increase with target depth.

Table 3. Planned H1 beamline octupoles strengths at the BioLEIR facility.

| Extraction H1 beamline octupoles | Unit  | OCT1   | OCT2   |
|----------------------------------|-------|--------|--------|
| Nominal strength                 | T.m⁻³ | 13,400 | 33,500 |
| Nominal pole tip field           | T     | 1.675  | 4.188  |
| Integrated strength              | T.m⁻² | 4,422  | 11,055 |
| Normalised strength              | m⁻⁴   | 2,000  | 5,000  |
| Integrated normalised strength   | m⁻³   | 660    | 1,650  |
Figure 5. The density profiles for the beam spot of the 440 MeV/u fully stripped Carbon ions shown in figure 4 at the target front plane, 10 cm in target, and 20 cm in target in both x-plane (a) and y-plane (b). The FWHM values in both planes were assessed at the target front plane. The beam profile, and therefore the corresponding FWHM value, in both planes increases slightly with target depth. No material was involved at the location where the beam in moving after the last quadrupole triplet at the end of H1 beamline, see figure 1.

5 Discussion on tail folding

The beam dynamics and multi-particle calculations were modeled from the LEIR extraction point to the end of the H1 beamline using the multi-particle tracking code MAD-X (Methodical Accelerator Design computer program, version X [10]). A beam of 3x10^5 particles was created using a distribution derived from the beam parameters at the LEIR extraction point.
Figure 6. Two-dimensional density distribution of the 440 MeV/u fully stripped Carbon ions beam at the target plane at the end of the H1 beamline. The beam spot is uniform over an area of $40 \times 40 \text{mm}^2$ (~20% of the beam), with a beam homogeneity of $\pm 2\%$ in the x-plane and $\pm 4\%$ in the y-plane. The uniform portion of the beam spot is surrounded by two higher-intensity walls.

The higher-intensity walls outside the $40 \times 40 \text{mm}^2$ uniform region (see figure 6) is produced by overshot tail-folding through octupoles focusing. The beam located outside the uniform area can be collimated directly after the quadrupole triplet at the end of the H1 beamline, keeping enough space between the collimator and the target in order to limit the effect of any unwanted secondaries on the irradiated target. Another possible approach could be the idea of using dodecapole magnets instead of octupole magnets. The dodecapole magnets generate an approximately uniform transverse distribution at the target location but with the advantage of producing smaller higher-intensity walls surrounding the uniform central region [8]. Both beam options, broad beam (octupole magnets ON) and pencil beam (octupole magnets OFF), with the required specifications were obtained by adjusting the quadrupoles strengths (see table 4). One of the quadrupole converters ($q_{h3}$) in the H1 beamline requires a polarity switch between pencil and broad beam optics (see table 4 (b)). More detailed studies should be carried in a next project stage to include error analysis and the design of the collimation system in front of the H1 irradiation point.

6 Conclusions

The first horizontal beamline (H1) employs octupole magnets to generate a uniform beam distribution at the target location. A rectangular beam area of $40 \times 40 \text{mm}^2$ is achieved, with a beam homogeneity of $\pm 2\%$ in the x-plane and $\pm 4\%$ in the y-plane, by adjusting the strengths of the oc-
Figure 7. The density profiles for the beam spot of the 440 MeV/u fully stripped Carbon ions shown in figure 6 at the target front plane, 10 cm in target, and 20 cm in target in both x-plane (a) and y-plane (b). The beam profiles in both planes increase slightly with target depth.

tupoles and quadrupoles. Such uniform irradiation fields are often necessary to irradiate biological samples (i.e. cell cultures). In addition, the H1 beam transport line is capable of providing a pencil beam with a FWHM of 4.3 mm in both planes. Furthermore, it was shown that the beam size of the broad beam does not change with target depth, which was achieved by matching the beam at the target planes and optimizing the magnets strengths.
Table 4. Maximum quadrupole gradients (G) for the common transport line and the horizontal extension H1 for both pencil and broad beams.

(a) Common beamline.

|      | qc1 | qc2 | qcb1 | qcb2 | qcb3 | qc3 | qc4 |
|------|-----|-----|------|------|------|-----|-----|
| G [T/m] | -2.5 | -0.4 | -7.3 | 16.4 | -6.3 | 8.2 | -6.4 |

(b) First horizontal extension H1.

|      | qh1 | qh2 | qh3 | qh4 | qh5 |
|------|-----|-----|-----|-----|-----|
| G [T/m] (Pencil Beam) | 4.0 | -5.0 | 1.2 | -4.9 | 14.9 |
| G [T/m] (Broad Beam) | 5.3 | -38.0 | -6.0 | -4.6 | 7.5 |

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