Design of ETOILE Medium Energy Beam line

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Abstract

Details of the geometrical and optical specificities of the medium energy beam line of ETOILE hadrontherapy plant project are presented.

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1 Introduction

The ETOILE synchrotron based Rhône-Alpes hadrontherapy installation project [1] leans on an injection layout that differs from two other projects considered a reference for ETOILE (due to the same LINAC plant being used) namely HICAT and TERA. The differences mostly arise from building arrangement.

For this reason the medium energy beam line (MEBL) that steers the 7 MeV/u beam from the LINAC exit down to the electrostatic septum needed some redesign effort for ETOILE.

Prerequisites

The injection layout of ETOILE has been worked out on the basis of room optimization inside the medical building [1] and is schemed on Fig. 1 ; it imposes the geometry and allows deriving the magnetic parameters necessary for designing the medium energy beam line (MEBL), that stretches from the beam stripper (BS) exit down to the downstream end of the injection electrostatic septum (ESeptum). The design we are concerned with here restrains in fact to that part of the MEBL that goes from the stripper exit down to the first magnetic septum ($MS1$) entrance, whereas the optics from $MS1$ down to the injection point into the ring is drawn from PIMMS layout.

As to the geometry of the line the design constraints are :

- On the one hand the LINAC is placed on a direction orthogonal to the ring injection straight section, on the other hand the injected beam is presented parallel to that straight section at the exit of the ESeptum. That yields 90 degrees total deviation for the MEBL,
- of which, 0.06 rad are assured by the ESeptum and 0.5 rad by the pair of magnetic septa ($MS1$, $MS2$) located right upstream (32.086 deg total).
- It results that the two additional identical bending magnets insure a deviation of 0.5054 rad = 28.957 deg each.
- In addition from the layout (Fig. 1) one draws the distances
  - from stripper to first bend entrance : 2.3162 m,
  - from exit of first bend to second bend entrance : 3.4497 m,
  - from second bend to first magnetic septum : 5.7524 m.

As to the optical structure, known parameters are

- achromatic line, $D_x = 0$ and $D_{x'} = 0$ at both ends ;

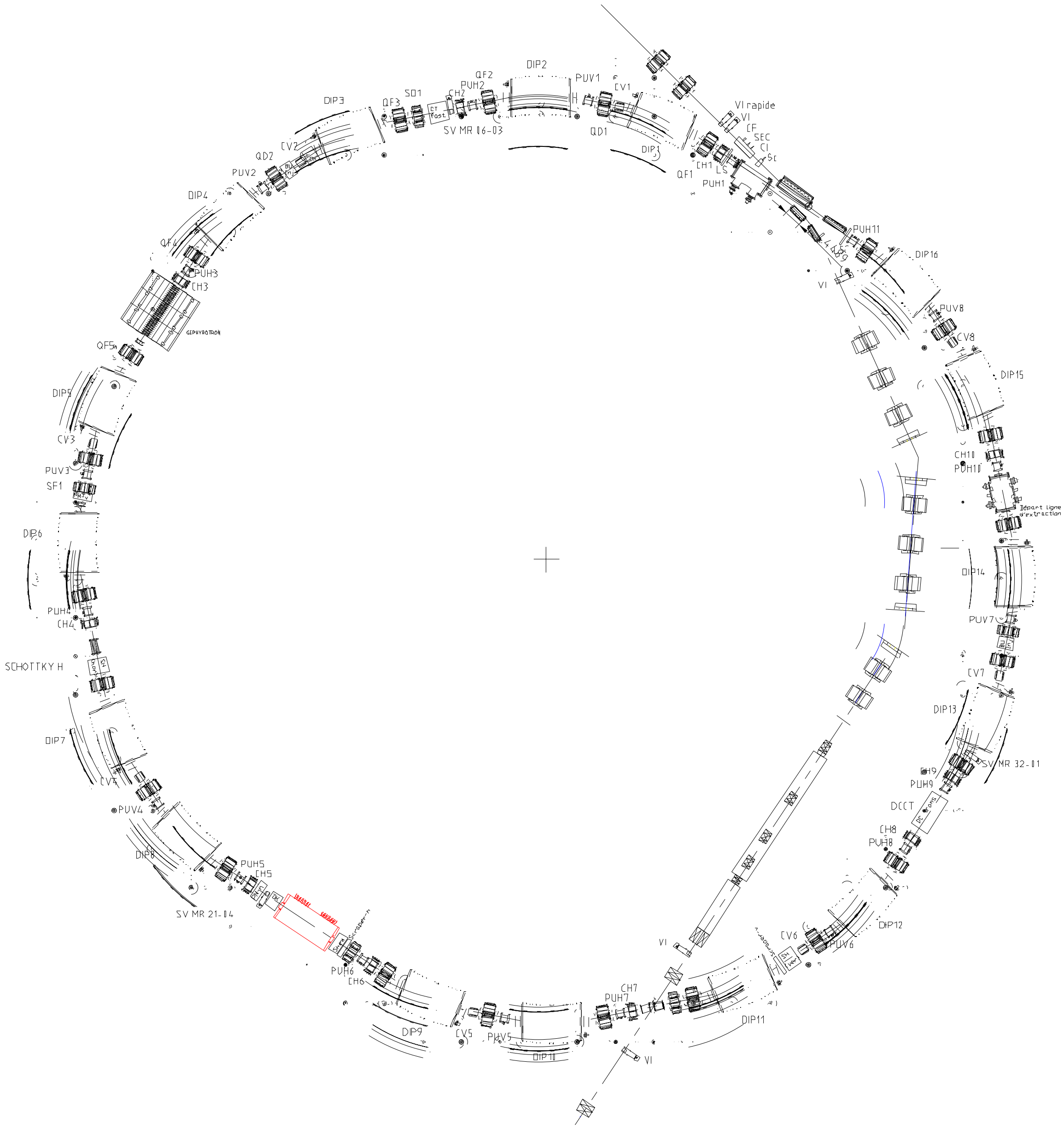

Figure 1: The ETOILE project synchrotron [2] and its injection line.

- starting optical functions, at the beam stripper right downstream of the 7 MeV/u LINAC [3] :

$$\beta_x = \beta_z = 0.19 \text{ m}, \ \alpha_x = \alpha_y = 0 \ ;$$

- final optical functions, at the downstream end of the ESeptum [2] :

$$\text{Carbon }, \beta_x = 8.53 \text{ m}, \ \alpha_x = -0.16, \ \beta_z = 5.7 \text{ m}, \ \alpha_z = 0,$$

$$\text{proton }, \beta_x = 7.03 \text{ m}, \ \alpha_x = -0.20, \ \beta_z = 3.75 \text{ m}, \ \alpha_z = 0 \ ;$$

- necessity for a horizontal beam waist at the location of a mass slit, right upstream of the second bend [3].

Beam parameters have been obtained from transport simulations through the LINAC structure, including space charge for the proton beam, that yielded [3] :

$$\text{Carbon } : \epsilon_x/\pi = \epsilon_z/\pi = 5 \ 10^{-6} \text{ m.rad}, \ \delta p/p = \pm 2 \ 10^{-3} \ ;$$

$$\text{proton } : \epsilon_x/\pi = \epsilon_z/\pi \approx 10 \ 10^{-6} \text{ m.rad}, \ \delta p/p = \pm 2 \ 10^{-3}.$$

2 MEBL design

The full MEBL length is 16.565 m. The magnetic arrangement is shown in Figs. 1, 2. and uses seven quadrupoles. that render the optics flexible enough for the six parameters to be adjusted. Following earlier design studies at GSI [4] room is provisioned for positioning mass slits at an horizontal waist right upstream of the second bend, as well as a debuncher cavity about 12 m downstream of the stripper foil.

However another solution is presented in App. 2 that requires only six quadrupoles. It has the advantage of the economy, and of leaving additional room for other equipments. It has the disadvantage of less degrees of freedom and tuning margins, and in addition it requests the first quadrupole to be 1.4 times stronger while the horizontal beta function reaches sensibly larger values at the start of the line (46 m instead of 36 m with 7 quadrupoles), which also entails higher sensitivity to defects.

The maximum quadrupole strength is $K_{max} = 3.9 \text{ m}^{-2}$, attained in $Q1$ (Tab. 2), and yields a weak maximum gradient of $G_{max} = 3.9 \times 0.763 \approx 3$ T/m with 0.763 T.m being the maximum rigidity, attained with 7 MeV/u Carbon.

Acknowledgements

This study has been performed in close collaboration with A. Tkatchenko, IPN-Orsay.

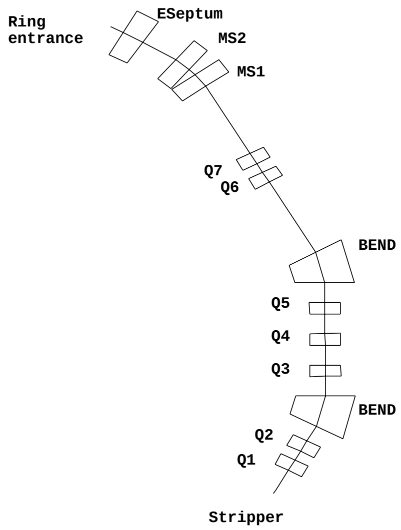

Figure 2: Synopsis of the medium energy beam line, from stripper exit to ring entrance.

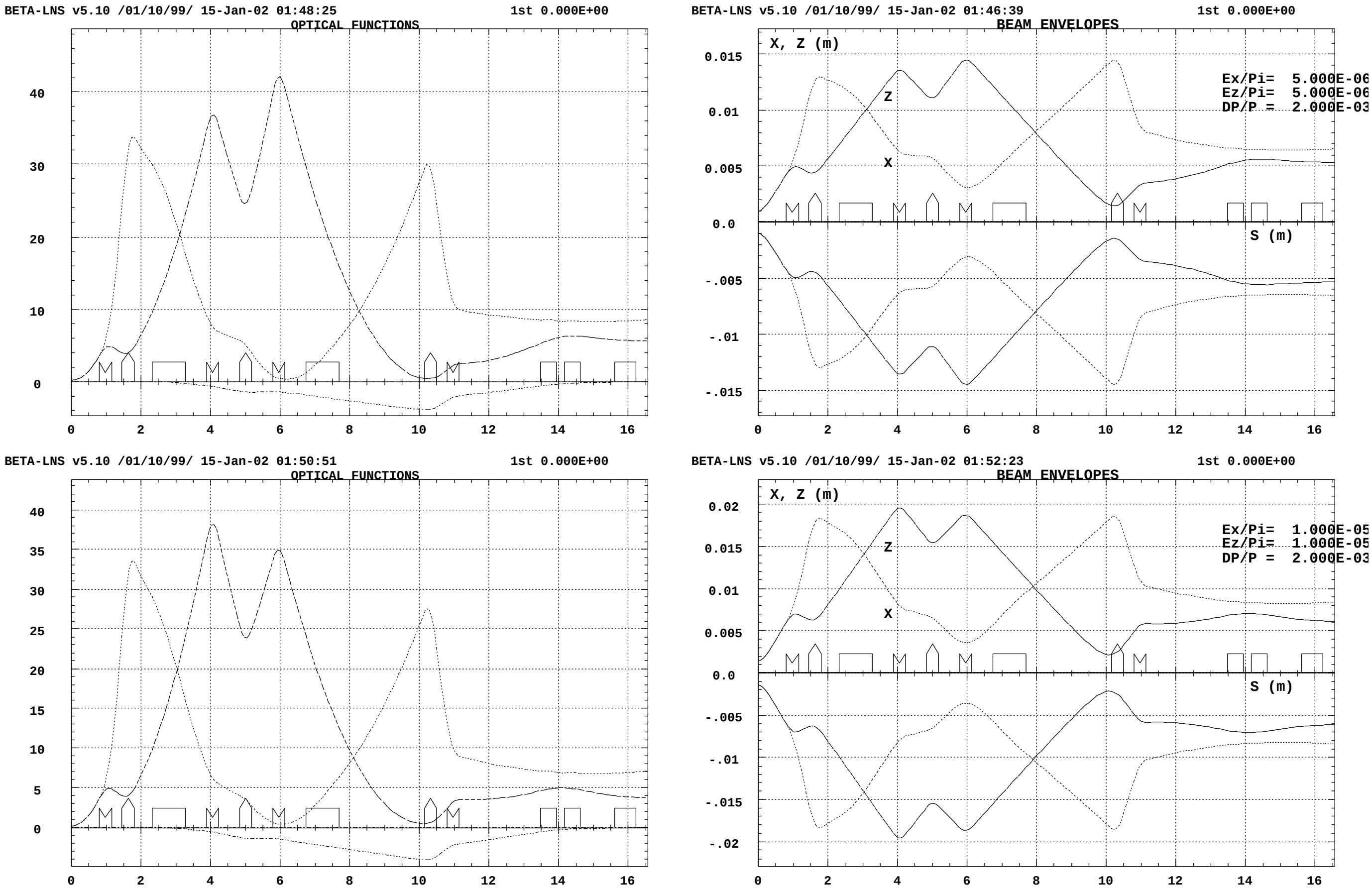

Figure 3: Optical functions and beam envelopes, Carbon (top, $\epsilon_x/\pi = \epsilon_z/\pi = 5\ 10^{-6}$, $\delta p/p = \pm 2\ 10^{-3}$ m.rad) and proton (bottom, $\epsilon_x/\pi = \epsilon_z/\pi = 10\ 10^{-6}$ m.rad, $\delta p/p = \pm 2\ 10^{-3}$).

Table 1: Position of optical element entrance along the MEBL, origin taken at stripper exit (Fig. 2).

	s (m)
Ring Entrance	16.565
ESeptum	15.615
MS2	14.165
MS1	13.490
Q7	10.774
Q6	10.104
BEND	6.731
Q5	5.781
Q4	4.831
Q3	3.881
BEND	2.316
Q2	1.454
Q1	0.804
Line Start	0

Table 2: Required characteristics of dipoles, and quadrupole strengths. All quadrupoles are 0.35 m long.

Dipole			
length	m	0.9653	
angle	deg	28.9572	
radius	m	1.91	
Quads			
		Carbon	*proton*
Q1		-3.9	-3.9
Q2		3.236	3.309
Q3	m^{-2}	-1.548	-1.637
Q4		1.927	1.738
Q5		-1.531	-1.357
Q6		2.697	2.680
Q7		-3.086	-3.097

Appendix : Six-quadrupole optics

The full MEBL length in this design is only 14.426 m, a little shorter than requested, which however has no significant impact on the feasibility. The six-quadrupole magnetic arrangement is shown in Fig. 4. That set of only six quadrupoles is flexible enough for the six parameters to be adjusted.

The maximum quadrupole strength is $K_{max} = 5.6$ m^{-2} which yields a weak maximum gradient of $G_{max} = 5.6 \times 0.763 \approx 4.3$ T/m with 0.763 T.m being the maximum rigidity, attained with 7 MeV/u Carbon.

Table 3: Position of optical element entrance along the MEBL in laboratory frame coordinates, origin taken at stripper exit (Fig. 2).

	x (m)	y(m)
Ring Entrance	-3.07845	12.34728
ESeptum	-2.25743	11.87123
MS2	-1.06701	11.04965
MS1	-0.64819	10.52329
Q6	0.46755	8.50690
Q5	0.87909	7.76316
BEND	1.35995	6.40093
Q4	1.35995	5.45093
Q3	1.35995	4.50093
BEND	1.12116	2.02619
Q2	0.70963	1.28246
Q1	0.29810	0.53873
Line Start	0	0

Table 4: Required characteristics of dipoles, and quadrupole strengths. All quadrupoles are 0.35 m long.

Dipole			
length	m	0.9653	
angle	deg	28.9572	
radius	m	1.91	
Quads			
		Carbon	*proton*
Q1		-5.585	-5.301
Q2		3.211	3.215
Q3	m^{-2}	1.167	1.039
Q4		-2.452	-2.378
Q5		2.732	2.780
Q6		-2.900	-3.130

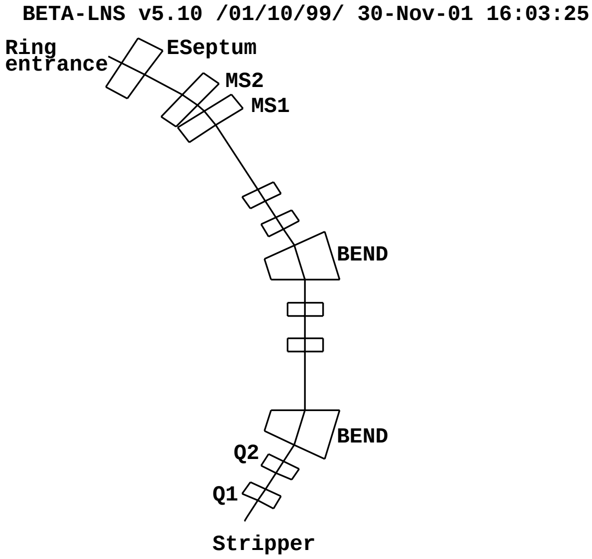

Figure 4: Synopsis of a 6-quadrupole version of the medium energy beam line, from stripper exit to injection electrostatic septum exit.

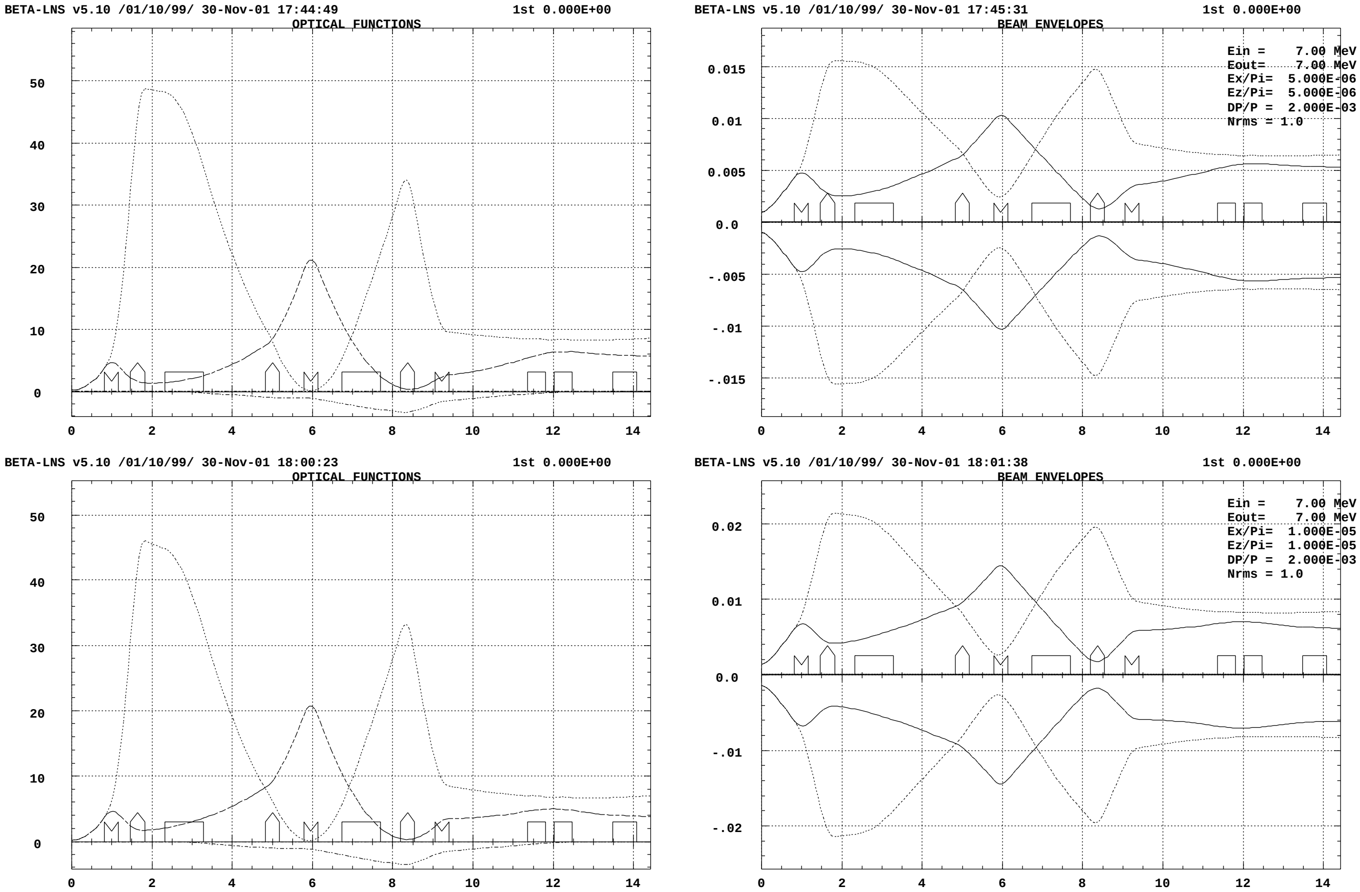

Figure 5: Optical functions and beam envelopes, Carbon (top, $\epsilon_x/\pi = \epsilon_z/\pi = 5\ 10^{-6}$, $\delta p/p = \pm 2\ 10^{-3}$) and proton (bottom, $\epsilon_x/\pi = \epsilon_z/\pi = 10\ 10^{-6}$, $\delta p/p = \pm 2\ 10^{-3}$).

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