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ETOILE* HADRONTHERAPY PROJECT, REVIEW OF DESIGN STUDIES

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Abstract

The Rhone-Alpes hadrontherapy facility project ETOILE is based on production of up to 400 MeV/amu carbon and 220 MeV proton beams using earlier CERN synchrotron design "PIMMS". The accelerator complex has necessitated several design studies relevant to the technical specificities of ETOILE, in support to cost evaluations. These studies are described and concern the optics of the low, medium and high energy beam lines, treatment room beam delivery, and the optimisation of 7 MeV proton injection.

1 INTRODUCTION

The Université Claude Bernard Lyon 1 launched in 1999 a project of a carbon ion hadrontherapy centre called ETOILE : Espace de Traitement Oncologique par Ions Légers Européen (European Light Ion Oncological Treatment Centre) [1], on the basis of two main reference projects, PIMMS [2] as to the synchrotron and HICAT [3] as to the Linac stage.

This paper presents various optics studies specific to the ETOILE facility, regarding the accelerator and beam lines, that have been undertaken in support to the preliminary technical design.

What follows is more an overview of the accomplished work, details can be found in reports referred to.

2 GENERAL PRESENTATION

Medical performance specifications have imposed the following specifications relevant to machine design :
• Variable energy accelerator, a synchrotron • Two ion sources for carbon ions and protons • Final energies for 2 to 27 cm penetration depth in water, i.e., C: 85 - 400 MeV/amu, p: 50 - 200 MeV • FWHM beam size at the patient within 4 to 10 mm, by steps of 2 mm • Maximum number of particles per spill at the patient: $^{12}C^{6+} \approx 4\,10^8$, protons $\approx 10^{10}$. • Scanning source to tumor isocentre distance greater than 3 m • Fast beam-stop (200 ms) based on deflectors.

A synchrotron based facility (Fig. 1) has been retained. Two sources produce ions that are steered through a low energy beam line (LEBL) to a linear accelerator (based on HICAT), and then through a medium energy beam line (MEBL) injected into the synchrotron (based on PIMMS) for acceleration to their nominal energy. The particles are

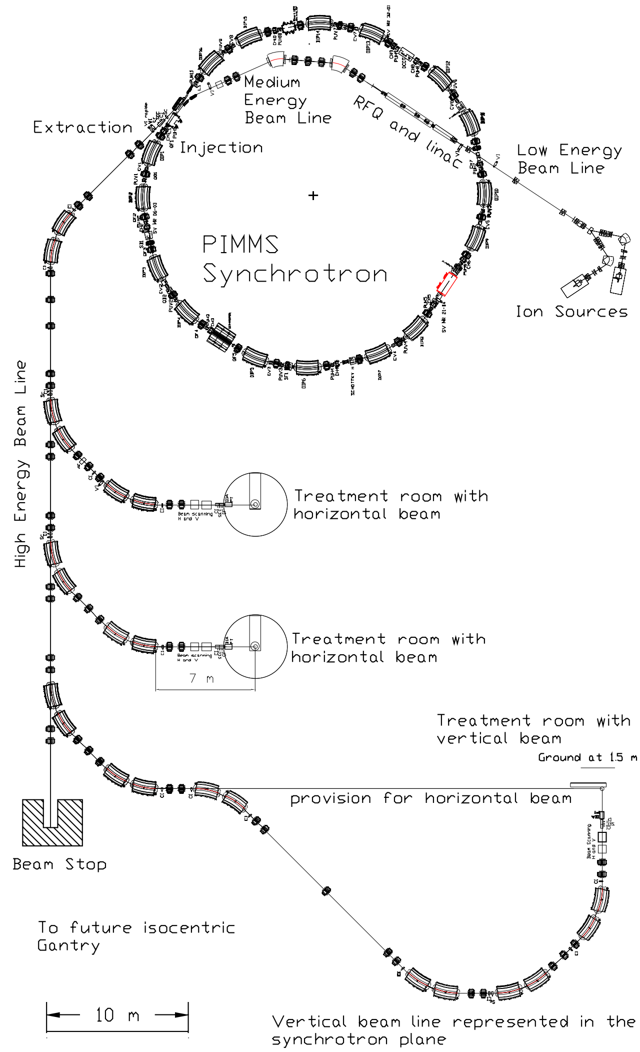

Figure 1: General structure of the facility

then extracted and transported along high energy beam lines (HEBL) to the treatment rooms arranged in a "fish-bone" structure, and delivered by a scanning system, or possibly a passive diffusion system.

3 SPECIFIC STUDIES

3.1 Injection line

LEBL - The beam from the source is analyzed by a magnetic spectrometer which is followed by a triplet of quadrupoles, making it possible to adjust the intensity in a range 1-1000. There is then a switching magnet which selects the source, downstream of which is a chopper that

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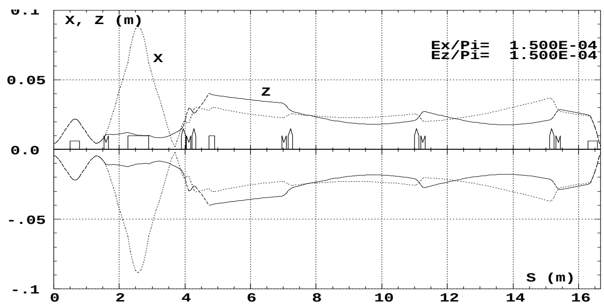

Figure 2: Beam envelopes in the LEBL (no space charge).

adjusts the period of the pulse injected in the RFQ.

Beam envelopes in the LEBL are shown in Fig. 2. The possibility of transport without losses, with space charge, of a H^{2+} beam (1 mA at 8 keV/amu) has been established by combining the quadrupoles in triplets, the beam then has a diameter of around 70 mm [4].

MEBL - The line starts from the Linac exit with a triplet that focuses the ions on the carbon foil stripper, followed by a double dipole deflection, and ends into the ring injection elements, namely two septum magnets followed by an electrostatic injection septum. The total deflection is

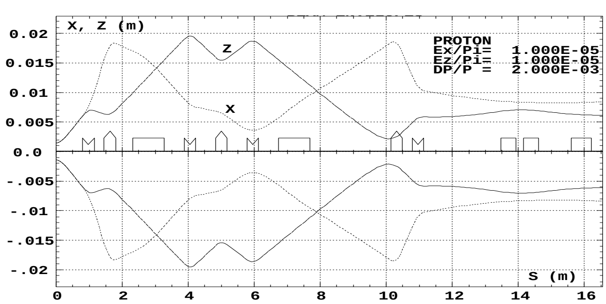

Figure 3: Beam envelopes in the MEBL (proton case).

90 degrees. The MEBL also houses analysis slits as well as a debuncher which reduces the momentum spread to $\pm 1.5\,10^{-3}$ [5]. Fig. 3 shows extreme envelopes [6].

7 MeV proton injection - ETOILE presents the specificity of an injection of a 7 MeV proton beam by contrast to the 20 MeV injection in PIMMS. Two limitations must be taken into account: 1/ acceptance of the ring imposed by the aperture of magnetic elements already defined in PIMMS, and 2/ space charge induced tune spread.

The first limitation is overcome by inferring the 7 MeV emittance from the emittance at 20 MeV ($12.5\pi\,10^{-6}$ m.rad) by a magnification factor equal to the ratio of the Lorentz coefficients $\beta\gamma$(20 MeV)$/\beta\gamma$(7 MeV) = 1.7. This ensures $21\pi\,10^{-6}$ m.rad emittance, well within the $30\pi\,10^{-6}$ m.rad carbon beam one, and guarantees the PIMMS' criterion of equal extracted emittances over the whole energy range. The second limitation disappears because the number of protons in each spill (10^{10} at the patient) is reduced by a factor of 2 compared to PIMMS value. The consequence of this is that the operating region in the tune diagram remains unchanged [2, Vol.II,Fig.7.5].

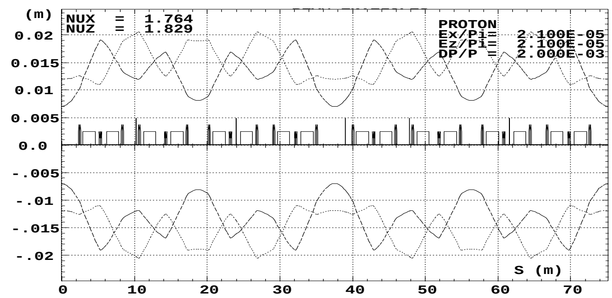

Figure 4: 7 MeV p-beam stored envelopes after injection.

In view of these results, a new multi-turn injection layout with 7 MeV protons has been optimized [7], in relation to the initial PIMMS scenario, without having to make any major changes to the injection parameters.

Finally, the sensitivity of the closed orbit to field errors is clearly greater than at 20 MeV. However the example of the MIMAS booster (injector for the SATURNE 2 synchrotron) demonstrates the feasibility of 130-turn injection of 390 keV protons without particular difficulty [8]. The closed orbit at injection could be brought from 10 mm before correction to 1 mm with correction.

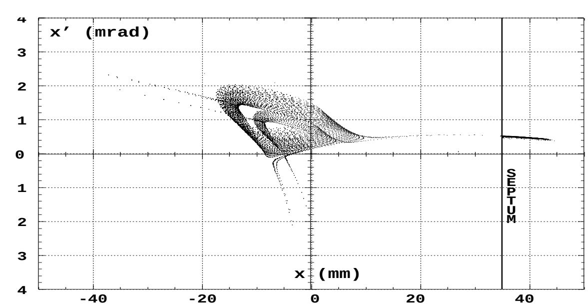

Figure 5: Horizontal phase space at extraction.

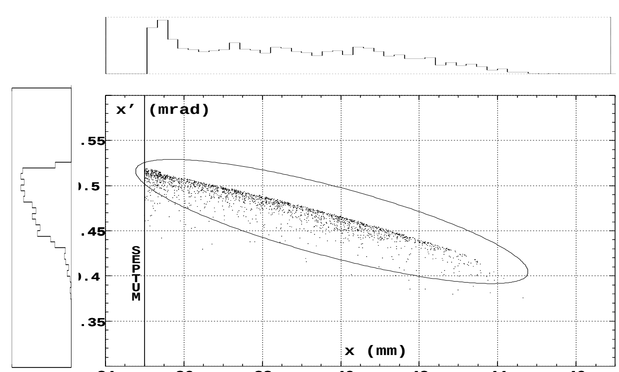

Figure 6: Extracted beam at entrance to the electrostatic septum.

Slow extraction - At extraction the horizontal tune is close to 5/3, a betatron core slowly pushes the beam into the resonance and an electrostatic septum deflects the wide spread particles into the extraction channel. The "Hardt" optics condition improves the extraction efficiency and the quality of the beam extracted. This concept of forced-acceleration extraction based on the use of a betatron core was developed and perfected 20 years ago for the SATURNE 2 synchrotron at Saclay [9]. The extraction process is easier to control with this technique as all the optical elements of the machine are kept constant, with the only dynamic system being the power converter of the betatron.

Simulations have been done, sketched in Figs. 5, 6) [10], and provide results consistent with PIMMS studies.

HEBL - A ”fishbone” structure has been chosen which is advantageous in terms of modularity, adjustment and possibility of extension. It makes the installation of additional rooms easier if this is required.

The 150 meters of lines are made up of three basic independent achromatic modules giving regular and repetitive beam envelopes, and enabling easy adjustment of the beam diameter in treatment rooms.

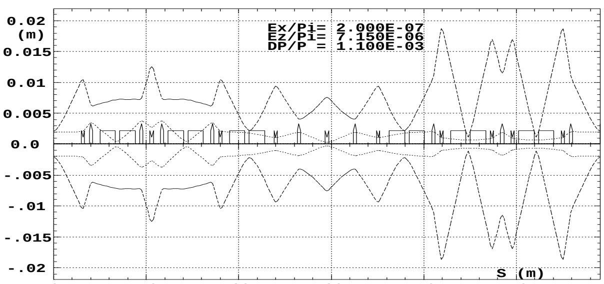

Figure 7: Typical envelopes in the 59 m long vertical beam line.

The 45 degree deflection of the extraction module houses a 200 ms beam chopper.

Scanning systems have been positioned downstream of the last deflection dipole on each line in order to minimize the final dipole air gap. It also makes maintenance easier and enables the use of identical dipoles in the high energy lines. On the other hand it leads to taller vertical beam line.

The optical conditions at origin of the HEBL are PIMMS ones, based on the characteristics of the slow extraction process, in particular the size of the beam at the origin of the high energy lines is: • in the horizontal plane: 10 mm total, regardless of the energy and the type of particles • in the vertical plane: 17.4 to 11.4 mm for carbon, from 85 to 400 MeV/amu ; 16.8 to 11.3 mm for protons, from 50 to 220 MeV • The total momentum dispersion is $1.1\,10^{-3}$.

A comprehensive study of the beam envelopes, as sketched in Fig. 7, has been carried out for all energy and diameter operating conditions [11] and has led to definition of the optical elements and the pumping and diagnostics system. In particular, the quadrupoles required are the same as those proposed for the PIMMS extraction line, with magnetic length 0.35 m and maximum field gradient 20 T/m ; the dipoles are new, of the C-type, air gap 0.056 m, nominal field 1.5 T, bending radius 4.231 m.

Passive mode distribution Although the ”active scanning” method is the irradiation technique planned for the ETOILE project, the possibility of ”passive” irradiation is to be allowed.

Following earlier studies and recent proposals regarding transverse beam uniformisation by non-linear lenses [12, 1] a principle optical design has been proposed for ETOILE (Fig. 8). Uniformity so achieved compares fairly well with

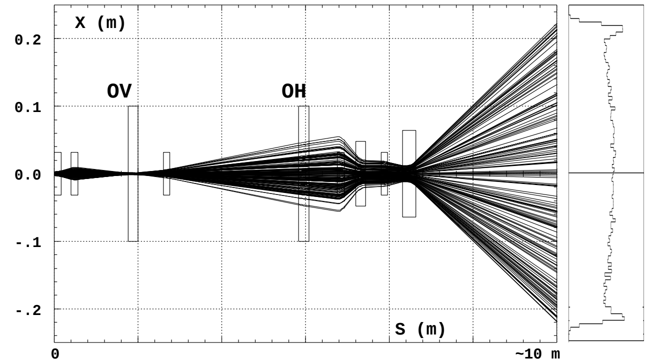

Figure 8: Uniformized cross-section at target, by octupole lenses OH and OV.

regular interceptive methods, and is moreover liable to improvement with higher odd-order non-linear lenses. In addition, being based on purely optical means it is fully non-interceptive.

4 ACKNOWLEDGEMENTS

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