ETOILE: The hadrontherapy project for Lyon (France)

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Abstract

The Université Claude Bernard Lyon 1 (UCBL) took the initiative in 1999 to ask a number of French doctors and physicists to draw up a specification for the creation of a Light Ion Hadrontherapy Centre. Under the auspices of this university and with the support of the local authorities and the Ministry of Research, a preliminary design [1] has been made in collaboration between UCBL, Commissariat à l'Energie Atomique (CEA/DSM) and Centre National de la Recherche Scientifique (CNRS/IN2P3). This project has taken full account of the experimental work carried out in Germany and Japan, and is part of a coordinated European approach, with similar projects developed in Austria, Germany, Italy and Sweden (ENLIGHT network).

1 INTRODUCTION

Light ion hadrontherapy has been tested in Japan (Chiba) and Germany (Darmstadt) for several years, following the pioneering work initially carried out at Berkeley. This method, which requires heavy-duty equipment, has demonstrated the advantages of these ions, in particular carbon ions, for the very accurate treatment of deep-seated tumours which are inoperable and radioresistant. ETOILE will be able to cure more than 500 of the 1000 patients treated each year (for whom existing treatments would have little effect), with a treatment cost lower than other cancer therapies currently in use.

The synchrotron is the kind of accelerator which best meets the medical specifications. Associated to the rasterscan technique developed and successfully applied at GSI, it permits to treat tumours with a complex shape, with a high flexibility: choice of energy/intensity of each spill in a wide range, spill triggering for mobile tumours, three-dimensional conformal irradiation. The optical structure of such an accelerator may be based on various types of solutions (lattice, injection, extraction) and requires a considerable amount of work. Such a task has been undertaken at CERN from 1996 to 1999 (PIMMS project) [2] before the start of ETOILE, leading to the detailed design of an optimized instrument. Following the Italian (CNA), Austrian (Med-Austron) and Swedish (Stockholm) projects, the PIMMS synchrotron has been adopted.

More generally, ETOILE has been designed by looking for common concepts and elements with the other European projects. The various elements (accelerator, beam distribution, building) have been examined to a detailed stage. The design is based on the most advanced projects (Italy, Germany) [3][4], on the actual experience of GSI and Orsay, and on the expertise of the research organizations (CEA, CERN, CNRS). Specific studies have been carried out (injection in the synchrotron, beam distribution, command/control, building, infrastructure, cost, staff and planning).

Table 1: Medical requirements

Ions	$^{12}C^{6+}$ and protons (possibility from p to ^{16}O)
Penetration	2 to 27 cm in water
Max. dose rate	2 Gy in 1 minute for 1 litre
Irradiation	rasterscanning
Treatment rooms	3 (2 with fixed horizontal beam, 1 with fixed vertical beam or gantry)
Patients	1000 patients /year
Operation	15 sessions/patient 0.5 hour/session 220 working days/year, 11 hours/day

Table 2: Technical specifications

Sources	2 ECR sources
Injector	RFQ+linac (GSI/Heidelberg)
Main accelerator	Synchrotron (PIMMS)
Distribution	Fish-bone structure
Energies	85-400 MeV/amu for carbon 50-200 MeV for protons
Extraction time	0.2 – 4 seconds
Nb of particles at patient, per spill	$4x10^8$ for $^{12}C^{6+}$ 10^{10} for protons
Cycle duration	1-10 seconds (gating)
Beam size	4-10 mm at patient (FWHM)

2 LAYOUT OF THE CENTRE

The general layout of the centre is presented Fig. 1 and Fig. 2. The accelerator, the beam lines, the treatment rooms and the control room are at the ground level ("machine level"). The doctor offices, treatment planning rooms, the scanners and NMR systems, as well as the accelerator conventional plant (power supplies, cooling system, technical offices etc.) are located at the first floor.

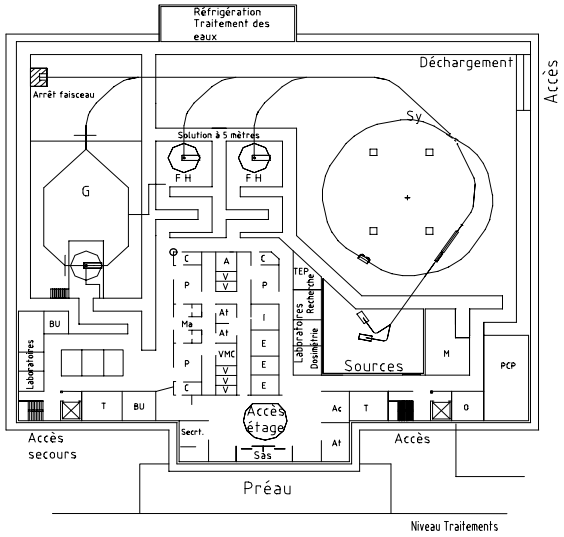

Figure 1: ETOILE layout (ground level). Scenario with a rotating gantry.

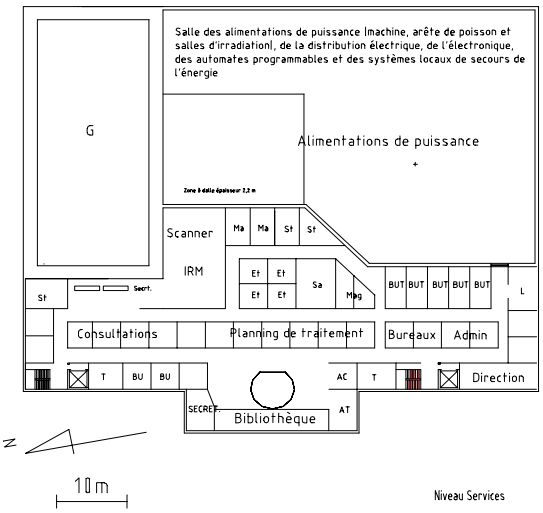

Figure 2: ETOILE layout (first floor).

2.1 Ion Production

The technology of ion sources is well established to provide protons, helium, oxygen and carbon at the required intensities. Carbon ions are provided by an ECR source commercially available like SuperNanogan, whose main advantages are its excellent long term stability (±1% for intensity over 2 weeks with 200 μA C^{4+}), its interchangeability and its reliability. Protons can be provided either by an ECR source or by a discharge source. H_2^+ or H_3^+ can be used to reduce the space charge effects. The required intensities are 125 μA for C^{4+}, 2.4 mA for protons and 1.2 mA for H_2^+.

2.2 Injection System

The injection system for ETOILE is based on that proposed for the GSI/Heidelberg project (HICAT) [3]. The injector of HICAT has been designed several years ago by the GSI team and the University of Franckfurt. This structure is as simple as possible (a single injector for several ion species), while providing a large range of adjustments, and is an optimized choice in terms of design and costs.

Table 3: Injection parameters

Energy	7 MeV/amu (proton to carbon)
Emittance	<1.2 π mm.mrad (total, normalized)
Δp/p	<±0.15% at 7MeV/amu
Intensity	105 μA for $^{12}C^{6+}$ 1.38 mA for protons
Injection time	33 μs (16 turns)
Repetition	< 1Hz
Duty cycle	$4\ 10^{-5}$

This injection system has also been chosen by the Italian and Swedish projects. It is composed of a low energy part (beam analysis, intensity adjustment, beam chopping), a RFQ, an IH-DTL and a medium energy beam line, including a stripper foil, where a debuncher is foreseen to reduce the momentum spread before injection in the synchrotron.

2.3 Synchrotron

Given the considerable amount of work and publications made by the PIMMS team, we will not give a detailed review of all the technical considerations which led to this optimized machine. We recall only some basic choices: multiturn injection (as proposed by CNA), transverse emittances equal over almost the whole range of extraction energies, use of a betatron core, invented and developed at SATURNE2 [5], to drive the beam to the resonance while keeping the optical parameters constant during extraction. The accelerating cavity is identical to that proposed in PIMMS and CNA and is based on a prototype tested in 1987 at SATURNE, and then transferred to CERN.

Injection from the HICAT linac has been optimized [6], taking into account two limitations: the acceptance of the ring and the proton space charge at 7 MeV (PIMMS was designed for 20 MeV). In fact, the second limitation disappears because the number of protons per spill required by ETOILE is half of what is required for PIMMS. The MIMAS experience at SATURNE2 has demonstrated also that the sensitivity to field errors, clearly greater at 7 MeV than at 20 MeV, could be easily overcome.

2.4 Beam Distribution

A fishbone structure has been chosen. It is advantageous in terms of modularity, tuning and possibilities of extension, in particular if additional treatment rooms are

needed in the future. The whole distribution system is made of independent achromatic basic modules giving regular and periodic beam envelopes. The beam quality and some further treatment techniques can be tested at the downstream end of the fishbone. On Fig. 1, the two rooms located on the right are supplied by an horizontal fixed line, and the room on the left is supplied by a gantry. The scanning system is located at the extremity of each line, immediately after the last deflection dipole. Just after the synchrotron extraction section, a chicane will stop the beam delivery in case of interlock.

2.5 Technical Devices

A new C-type dipole has been studied for the distribution lines. All the other elements are identical or similar to those of PIMMS.

The vacuum system is based on industrial type criteria to maximize reliability and efficiency: the desorption rate is 10^{-7} Pa.m.s^{-1}, corresponding to a clean non-backed chamber; the synchrotron system is not baked but bake-able, in event of accidental rise of the pressure; ion pumps are used in the ring, which require no maintenance. For example, the pressures are 5.10^{-7} Pa in the synchrotron and 10^{-5} Pa in the high energy beam lines.

A large amount of beam diagnostics have been foreseen along the machine (intensity, position of the centre of gravity, transverse profiles, on-line dose control), in order to guarantee the quality, the reliability and the traceability of the operation.

2.6 Control System

Its design has been based over commercially available components. However, in view of the rate of development in this field, the definitive choices have to be made at the construction stage. The system can be divided into two parts.

The accelerator control system is based on established solutions: VME for interfacing, VXI for the RF and EPICS for the software.

The treatment control system, responsible for supplying the correct dose to the patient, and based on VME for the hardware interfaces, workstations for the operator interface and Ethernet for communications.

The system will include the whole computing of the centre, including databases (accelerator and treatment data, archive, high volume storage and backup).

3 BUILDING AND INFRASTUCTURE

The lower floor ("treatment") is dedicated to reception, treatment rooms and machine. The upper floor ("service") is designed to house the medical services and auxiliary services (electrical distribution, power supplies, cooling, ventilation). In case of a network failure, a 250 kVA Uninterruptible Power Supply (UPS) has been foreseen, with 15 seconds independent operation and a return of 300 kVA after a few seconds by a generating set. It is essential to protect sensitive equipment such as filaments of RF tubes and to back up data about treatment, radiological control, imaging and command/control.

4 COST AND PLANNING

The cost of the different subsystems is given table 3 for the two options (with and without gantry). The construction of the facility is planned over 5 years. A 6th year will be dedicated to machine testing, to validation of the treatment system and to administrative licensing for treatment.

Table 3: Capital costs

Capital costs (november 2001)	without gantry (M€)	with gantry (M€)
Production of ions, linear accelerator and low energy beam lines.	8.83	8.83
Synchrotron	6.45	6.45
Distribution + rasterscanning	4.68	10.21
Control/computers	8.25	9
Buiding, infrastructures, including project management	23.2	24.6
Equipement for rooms	8.23	8.23
Cost of development staff	15	15
Contingencies 7%	5.22	5.74
Total cost	79.86	88.06

5 ACKNOWLEDGMENTS

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