DESIGN OF A BEAMLINE FROM CYRCé FOR RADIOBIOLOGICAL EXPERIMENTS

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Abstract

The PRECy project (Platform for Radiobiological Experiments from CYRCé) foresees the use of a 16-25 MeV energy proton beam produced by the recently installed TR24 cyclotron at the Institut Pluridisciplinaire Hubert Curien (IPHC) of Strasbourg for biological tissues irradiation. One of the exit ports of the cyclotron will be used for this application along with a combination magnet. The platform will consist of up to 3 or 5 experimental stations linked to beamlines in a dedicated 15 m x 13 m area next to the cyclotron vault. One of the beamlines will receive proton beams of a few cm diameter at intensities up to 100 nA. The status of the design of the first beam line is presented. The characterization of the proton beam parameters has been performed using the quad scan method. TraceWin and COSY Infinity codes allowed simulating the beam envelopes and defining the electromagnetic equipment that will compose the beamline.

INTRODUCTION

In October 2013, the Institut Pluridisciplinaire Hubert Curien (IPHC/CNRS) of Strasbourg inaugurated its brand new circular accelerator manufactured by ACSI (CAN) [1]. This cyclotron, called CYRCé (*Cyclotron pour la Recherche et l'Enseignement*), works at energies between 16 and 25 MeV for intensities up to 500 µA (Fig. 1).

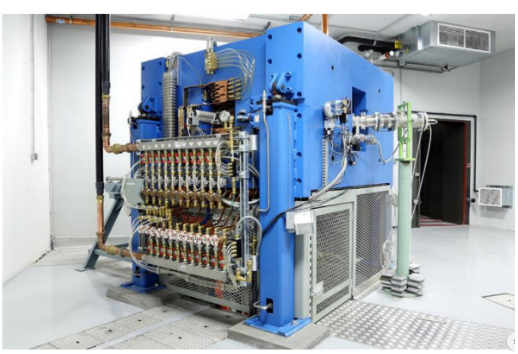

Figure 1: Picture of CYRCé in the casemate.

The accelerator mainly delivers ^{18}F and ^{64}Cu radioelement but also ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{124}I, ^{64}Cu, ^{68}Ge, ^{76}Br, ^{89}Zr for positron emission tomography (PET) and ^{123}I, ^{111}In, ^{67}Ga, ^{57}Co, ^{99}mTc for single-photon emission computed tomography (SPECT).

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PRECy

A Multi-Phase Project

The PRECy project aims at developing a platform for radiobiological studies from CYRCé. They will be performed for a better understanding of the RBE (Relative Biological Effectiveness) *in vitro* and *in vivo* in small animals (mice) and the study of combination treatment with chemotherapy and proton therapy. The project is divided into two phases over the years 2015 - 2020:

- Phase I (2015-2017): Extraction and Transport of 25 MeV proton beams, out of the existing casemate, to the experimental low energy stations dedicated to *in vitro* studies of the interaction of protons with the cells. By slowing down the beam, it will be possible to cover a range of energy ranging from a few hundred keV to 25 MeV and allow experimental measurements of the RBE on cell cultures and more fundamentally on the molecules constituting the living. The goal is to better understand the effects of the dose deposition at low linear energy transfer (LET) where biological effects are most important.
- Phase II (2018-2020): Extraction, acceleration of protons up to 70 MeV and beam transport to the experimental halls of high energy radiation biology for the *in vivo* study (small animal). The acceleration system should allow to vary the energy of the beam and scanning a surface to enable a dose deposition in a volume (tumor) defined.

At low energy (Phase I), it will be possible to measure the biological effects *in vitro* at the Bragg peak (at the level of the tumor) and *in vivo* in subcutaneous tumors implanted in small animals. The post accelerating protons up to 70 MeV (Phase II) will allow measuring biological effects at low linear transfer, upstream of the Bragg peak (before the tumor) and thus to study the effects of radiation on healthy tissues crossed during treatments. In addition, this power increase will work *in vivo* orthotropic tumors.

rpPET Beamline

rpPET is a joined collaboration between IPHC and the Paul Strauss Centre [2] which started in 2015 for a period of 36 months. It consists in studying the relationship between the physical dose and biological effects in a proton therapy in mice by Positron Emission Tomography.

The rpPET beamline is entirely located inside the casemate and is composed of collimators, Faraday cups and of a steerer.

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THE DIPOLE SWITCHER MAGNET

A dipole magnet manufactured by ACSI is located at one of the exits of CYRCé and allows 2 extraction beamlines with a deflection of +/- 22 degrees: one for rpPET and one for PRECy. It is used as a combination magnet to accept the various extracted energies (and entrance angles) and also acts as a switching magnet to bend the beam down either of the two beamlines. Typical operating values are ~0.75 T for the field and around 120 A for the current.

BEAM PARAMETERS

Beamline Requirements for PRECy

The beamline must fulfill the following conditions:

- The particle used by the system is the proton,
- The intensity available must be from 0,01 pA to 100 nA,
- The energy deposited must be constant (< 1%),
- The irradiation should be performed over a surface of 10 to 20 mm diameter, and must be homogeneous in depth,
- Passive modulated proton beams system,
- Irradiations can be done vertically.

CYRCé parameters

To design and define the optical elements mandatory to provide an efficient beam through this beamline, the proton beam delivered from the cyclotron has to be clearly characterized. Table 1 presents the physical parameters of the beam extracted from the cyclotron.

Table 1: CYRCé Beam Parameters

Parameter	Value
Particle	H^+
Intensity (µA)	10^4 pps – 400
Max energy (MeV)	24.4
Momentum (MeV/c)	218.033517
γ-1	0.026644717
β	0.226346713
Bρ (T.m)	0.727281529
Time Structure	CW (85 MHz RF)
Beam profile	Gaussian

At this point, no clear information was given concerning the emittances and their uncertainties. Therefore, measurements were necessary to estimate them.

EMITTANCE MEASUREMENTS

The determination of the beam transverse emittances can be performed by different methods [3]. A first attempt was done by Degiovanni et al. [4] using Gafchromic™ EBT3 films. Another method, the quad scan technique, uses the combination of quadrupole(s) together with profilers.

Experimental Setup

It consisted of a doublet of quadrupoles (QA-QB) and 2 profilers (DIAG 1-2) (Fig. 2). Measurements were performed for protons at kinetic energies of 18 MeV and 25 MeV and at intensity of few tens of nano amperes.

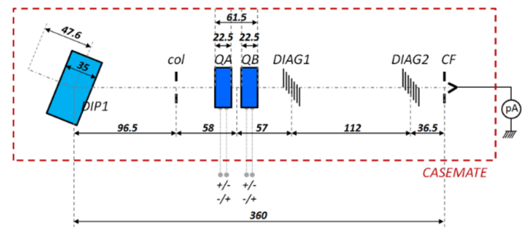

Figure 2: The quad scan setup (distances are in cm).

Results

Some of the measured beam profiles presented multiple peak structures and/or were out of axis according to the intensity applied to the quadrupoles. The fitting process of the data was done considering only the single peak curves. Corrections were applied to the ones being out of axis. An overall estimation for the emittances at a proton energy of 25 MeV gave (rms) $\varepsilon_x = 1.90 \pm 0.25\ \pi$ mm.mrad and $\varepsilon_y = 3.71 \pm 1.35\ \pi$ mm.mrad. Multiple peak structures were observed in a greater number at 18 MeV which made the estimation of the emittances difficult at such energy (Fig. 3). These structures were always present in the horizontal plane.

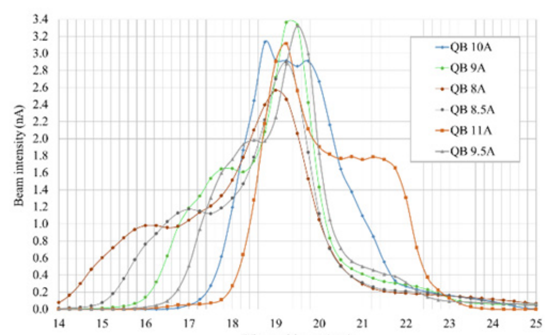

Figure 3: Beam profile at 18 MeV.

Discussions

These multiple peak structures could come from two causes: two different dipole and foil settings were used for the different DIAG positions and measurements in the horizontal plane may not be precise due to re-centering. Also, more than one proton energy could actually be extracted from the cyclotron due to foil positions and the extraction angles. To investigate further the phenomenon, simulations of the beam envelopes were performed. Three different cases were simulated and combined: a proton beam of 25 MeV (case 1), of 24.75 MeV and being horizontally off axis of – 3 mrad (case 2) and of 25.25 MeV and being horizontally off axis of + 3 mrad (case 3).

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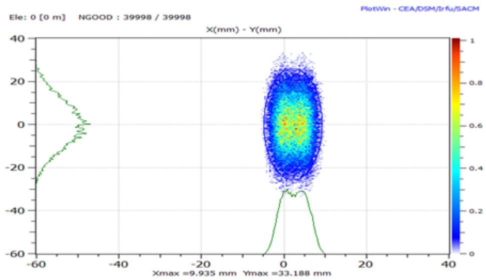

Figure 4: Multiple peak structure simulated.

The combination of the different cases confirmed the formation of a multiple peak structure and a shift of the beam profiles (Fig. 4). Other types of emittance measurements are foreseen in September 2016, using slits.

BEAMLINE DESIGN

Several configurations are possible once the beam exits the casemate: it can either be split using a switching dipole or reach the different experimental stations by a 'fishbone' layout (Fig. 5).

Figure 5: Possible layouts of the beamlines.

The use of a switching dipole after the casemate has been retained as it eases any other experimental station and beamline to be setup without adding a dipole each time. A 5-exit switching dipole is under discussion here.

Beam Optics

Preliminary simulations of the beamline were performed using the values given by [4] for the emittances (Table 2).

Table 2: Beam Parameters for Simulations

Parameter	Value
Emittances, ε_x / ε_y (4rms)	17 / 5 π mm mrad
Beam divergence, Δx / Δy	1.4 / 0.4 mrad
Beam size, σ_x / σ_y	3.03 / 3.12 mm
Dp/p (rms)	1 %

The two conditions set up on the transport codes were: beam waist at the diagnostics positions and position/angular achromaticity at the second dipole. TraceWin [5] and COSY Infinity [6] showed similar results. According to the codes, beam sizes of less than 20 mm can be achieved at the casemate wall using either a doublet or a triplet. Field gradients of the quadrupoles do not exceed 5.13; 4.38 T/m (QP1; QP2) when using the doublet and 2.4;1.71;1.77 T/m (QP1; QP2; QP3) when using the triplet configuration. The use of a doublet seems to be sufficient to manage the beam inside the casemate.

Equipment

The main objective of the beamline is to ensure the good quality of the proton beam before it reaches the experimental room. While obtaining more accurate values concerning the transverse emittances to refine the beam transport simulations, a list of equipment that will compose the first section of the beamline was established (Fig. 6). The main constraints when designing the beamline is to leave at least one-meter gap somewhere to allow maintenance operations to take place when necessary.

Beam manipulation devices

- Quadrupoles. It is foreseen to use new magnetic quadrupoles in the casemate to ensure good quality and avoid maintenance issues near the cyclotron during operation periods. Quadrupoles to be used will have magnetic length of about 225 mm and aperture of 30 mm. These characteristics are subject to slightly change according to the emittances that still to be confirmed and/or updated.

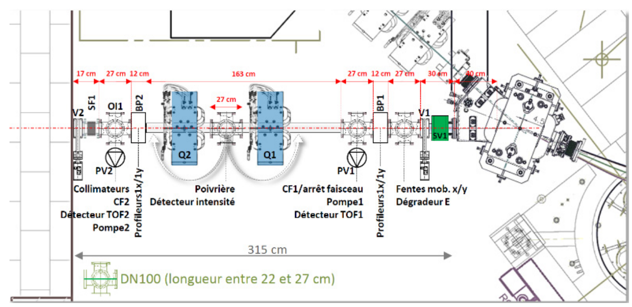

Figure 6: Elements composing the beamline. Q1/Q2: quadrupole 1/2. SV1: steerer.

- Steerer. The extraction process of the beam from the cyclotron can induce off axis beam propagations. Therefore, a steerer is necessary to ensure the good alignment of the beam before it reaches the optical devices.
- Other devices will be positioned on the beamline to impact the protons such as degraders, collimators or/and slits to shape the beam before it enters the focusing system or the wall pipe. Between four and five cross boxes will implement the beamline for these purposes.

Beam diagnostics Profilers will be positioned before and after the quadrupoles to check the good alignment of the beam. In case of misalignment the steerer will correct its position. Faraday cups will measure or stop the beam in case of emergency. TOF detectors (Pepperpot) would also be added along the beamline.

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