DESIGN OF A BEAMLINE FROM A TR24 CYCLOTRON FOR BIOLOGICAL TISSUES IRRADIATION

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Abstract

The PRECy project foresees the use of a 16-25 MeV energy proton beam produced by the recently installed TR24 cyclotron, CYRCé, 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 5 experimental stations linked to beamlines in a dedicated 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.

PRECY

The Institut Pluridisciplinaire Hubert Curien (IPHC/CNRS) of Strasbourg recently 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. 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).

Goals

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 first objective consists in designing a beamline to extract and transport the 25 MeV proton beams, out of the existing vault, 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 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 have a better understanding of the effects of the dose deposition at low linear energy transfer (LET) where biological effects are most important.

At low energy, 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. A second phase of the project aims at post accelerating protons up to 70 MeV and allows 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 would work *in vivo* orthotropic tumors.

rpPET Beamline

Prior to the development of this radiobiological platform, a first beam line was set up for *in vivo* studies. 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 proton therapy in mice by Positron Emission Tomography.

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

THE COMBO/SWITCHER MAGNET

A dipole magnet manufactured by ACSI is located at one of the exits of CYRCé and allows two extraction beamlines with a deflection of +/- 22 degrees: one dedicated to rpPET and the other one to the PRECy project. It is used as a combination magnet to accept the various extracted energies (and entrance angles) and 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.

BEAM PARAMETERS

Beamline Requirements for PRECy

The beamline must fulfill the following conditions:

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

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 known physical parameters of the beam extracted from the cyclotron.

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Table 1: CYRCé Beam Parameters

Parameter	Value
Particle	H^+
Intensity (nA)	<100
Max energy (MeV)	25.0
Bρ (T.m)	0.72
Time Structure	CW (85 MHz RF)
Beam profile	Gaussian

As no clear information was available concerning the transverse emittances of the beam and their uncertainties at this stage, its characterization was necessary.

BEAMLINE DESIGN

Emittances Characterization

The determination of the beam transverse emittances can be performed by different methods [3].

Degiovanni et al. [4] used a first method, consisting of using Gafchromic™ EBT3 films to obtain an image of the beam profile from the irradiation. The collected images were then numerically reconstructed and the FWHM were evaluated. This method gave emittances of:

$$\varepsilon_x^{rms} = 4.25\ \pi \text{ mm mrad}$$
$$\varepsilon_y^{rms} = 1.25\ \pi \text{ mm mrad}$$

To confirm these values and aiming to get more precise estimations, another method to determine the emittances was used by the IPHC teams. This method, called the "quad scan method", consisted in using the combination of quadrupole(s) together with profiler(s). A doublet of quadrupoles and 2 profilers were then used to perform the measurements. Profilers were located at 57 cm and 169 cm away from the centre of the doublet.

The intensity of the beam was collected as a function of the current applied to the coils of the quadrupoles QA or/and QB. Thus the beam size was plotted versus the quadrupole strength (Fig.1). From the parabolic plots, the emittance-related coefficients were calculated.

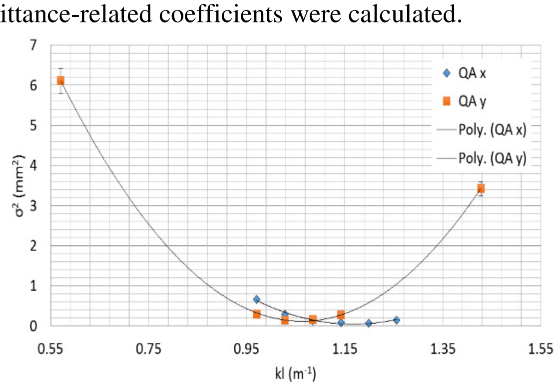

Figure 1: Beam size values according to the strength of the quadrupole QA, 25 MeV.

Some tuning difficulties were encountered during many of the measurements (dipole settings, foil positions) and impacted the results. Moreover multiple peak structures were observed in some profiles during measured contributing in giving high uncertainties in the estimated values. Nevertheless emittances were calculated to be:

$$\varepsilon_x^{rms} = 1.9 \pm 1.3\ \pi \text{ mm mrad}$$
$$\varepsilon_y^{rms} = 3.7 \pm 1.4\ \pi \text{ mm mrad}$$

Following these results, additional beam tests were planned. They were performed using a moving slit, a profiler and a grid. Figure 2 shows an example of the set of data measured while the slit is in vertical position.

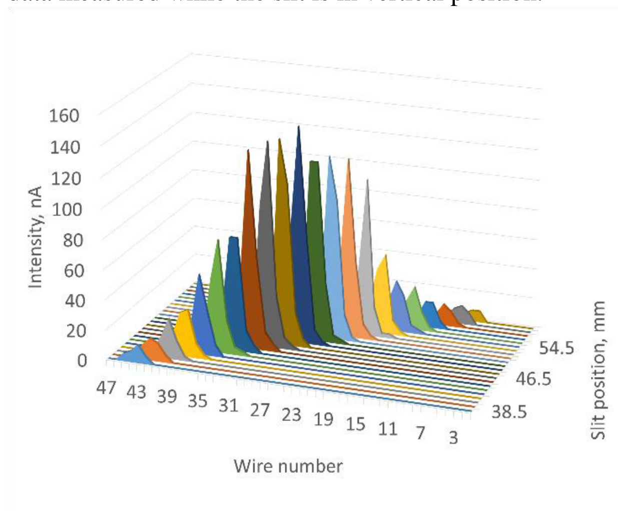

Figure 2: Intensity measured on the wires of the grid (vertical position) for proton energy of 25 MeV.

Upper limits of the emittances could be estimated:

$$\varepsilon_x^{rms} \leq 4.8 \pm 0.5\ \pi \text{ mm mrad}$$
$$\varepsilon_y^{rms} \leq 5.2 \pm 0.5\ \pi \text{ mm mrad}$$

An ultimate measurement campaign took place recently at the IPHC. It was performed by the University of Bern. Their method consisted in using a system called UniBEaM. This technique relies on a set of four detectors each made of a doped silica and optical fiber [5]. Preliminary estimations give emittances of (25 MeV) [6]:

$$\varepsilon_x^{rms} = 2.8 \pm 0.2\ \pi \text{ mm mrad}$$
$$\varepsilon_y^{rms} = 5.8 \pm 0.2\ \pi \text{ mm mrad}$$

Although each method gave different set of values for the emittances, few conclusions can be drawn:

- The emittance is bigger in the vertical plane than in the horizontal one (unlike in the first method perhaps due to x/y axis confusion when analyzing the foils);
- The ratio between both emittances is close to 2;
- The emittances are lower than 5 π.mm.mrad in both planes.

Beam Optics

TraceWin [7] was used to make the design of the beamline. To consider the most critical incoming beam, the upper limits of the emittances were applied to the code up to now.

According to the simulations, a doublet of quadrupoles is sufficient to properly focus the beam before it enters the 2-meter thick wall and reaches the experimental room (Fig 3).

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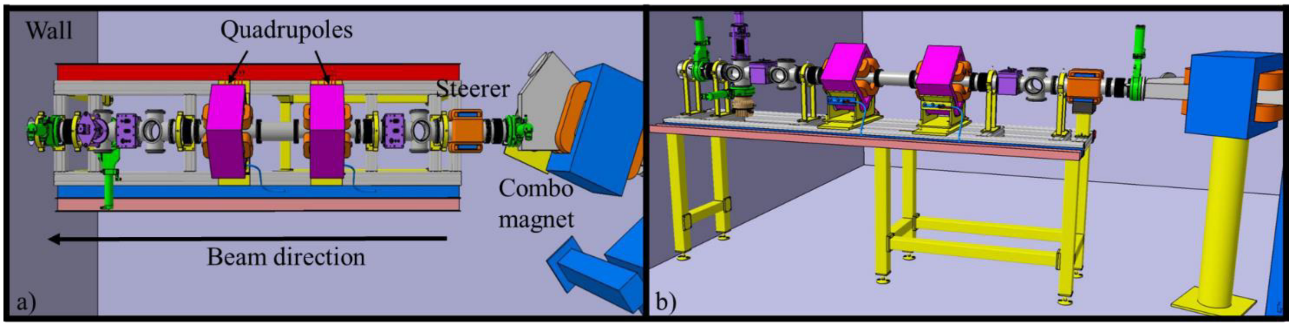

Figure 4: Top (a) and perspective view (b) of the foreseen PRECy beamline.

The distance between the combo dipole and the wall of the vault is 3.15 m. Thus one has to make sure all the necessary equipment fit inside this length.

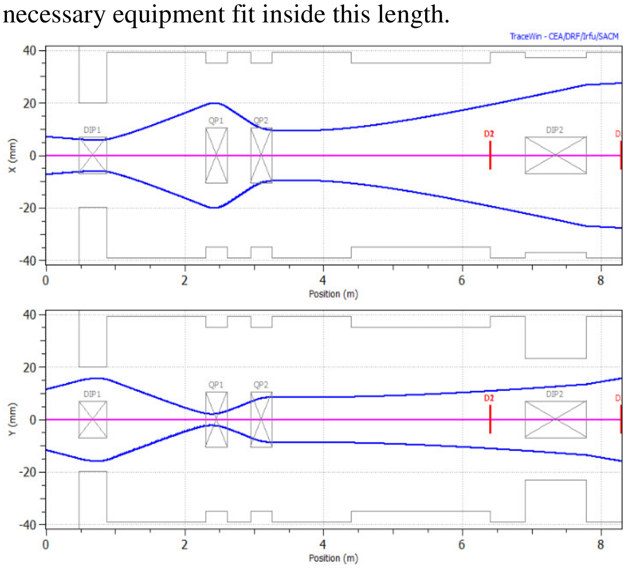

Figure 3: Transverse beam envelops, horizontal (top) and vertical (bottom) (3σ).

Equipment

The main objective of the beamline is to ensure the good quality of the proton beam before it reaches the experimental room. A list of equipment that will compose the first section was established. The main constraints when designing the optical line was to leave at least one-meter gap somewhere to allow maintenance operations to take place when necessary. Figure 4 shows the layout of the beamline inside the vault.

Beam manipulation devices

- To ensure good beam quality and avoid maintenance issues near the cyclotron during operation periods, quadrupoles located inside the vault will be built on this purpose. They will be 302 mm long and have an aperture of 78 mm.
- HV Steerer. The extraction process of the beam from the cyclotron can induce off axis beam propagations. Therefore, a steerer is necessary to ensure the alignment of the beam before it reaches the optical devices.
- Other devices will be positioned on the beamline to impact the protons such as collimators or/and slits if necessary to shape the beam before it enters the focusing system or the wall pipe. Between three and four cross-chambers will be implemented in the beamline for these purposes.

Beam diagnostics

- Profilers will be positioned before and after the quadrupoles to check the alignment of the beam. In case of misalignment, the steerer will be used to correct the position of the beam. Faraday cups will measure the beam current and used to stop the beam in case of emergency.

Beyond the Vault

A 5-exit dipole is foreseen after the cyclotron vault with the following angles of deflection: 0°, ±22° and ±40°.

ACKNOWLEDGMENT

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