Transverse beam emittance studies of the CYRCé TR24 cyclotron

E. Bouquerel, E. Traykov, K.P. Nesteruk, S. Braccini, T.S. Carzaniga, C. Mathieu, M. Pellicioli, M. Rousseau, C. Ruescas, J. Schuler, et al.

Transverse beam emittance studies of the CYRCé TR24 cyclotron

E. Bouquerel[a,*], E. Traykov[a], K. P. Nesteruk[b,1], S. Braccini[b], T. S. Carzaniga[b], C. Mathieu[a], M. Pellicioli[a], M. Rousseau[a], C. Ruescas[a], J. Schuler[a], S. Vichi[b,c]

[a] *IPHC, UNISTRA, CNRS, 23 rue du Loess, 67200 Strasbourg, France*
[b] *Albert Einstein Center for Fundamental Physics (AEC), Laboratory for High Energy Physics (LHEP), University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[c] *Department of Industrial Engineering, University of Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy*

Abstract

The PRECy project foresees the use of a 16-25 MeV energy proton beam produced by the TR24 cyclotron, named CYRCé, recently installed at the Institut Pluridisciplinaire Hubert Curien (IPHC) in Strasbourg for research in radiation biology. 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 located 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. In order to characterize the beam extracted from the cyclotron, the transverse beam emittance was studied by means of different methods.

Keywords: `Beam emittance`, `Diagnostics`, `Cyclotron`

1. Introduction

The Institut Pluridisciplinaire Hubert Curien (IPHC/CNRS) in Strasbourg recently inaugurated its brand new circular accelerator manufactured by ACSI [1]. This cyclotron, called CYRCé, works at energies between 16 and 25 MeV with

*Corresponding author
Email address: `elian.bouquerel@iphc.cnrs.fr` (E. Bouquerel)
[1] Currently at Paul Scherrer Institut, Switzerland

intensities up to 500 μA. It can produce radioisotopes for positron emission tomography (PET) (^{11}C, ^{13}N, ^{15}O, ^{18}F,^{124}I, ^{64}Cu,^{68}Ge, ^{76}Br,^{89}Zr) and for single-photon emission computed tomography (^{123}I, ^{111}In, ^{67}Ga, ^{57}Co, ^{99m}Tc). Recently a new project arose with the aim of developing a Platform for Radiobiological Experiments using protons produced by CYRCé (PRECy). This project is driven by a collaboration of physicists and biologists. Its objective is to allow a better understanding of the effect of proton radiation on the living matter. The specificity of the PRECy project at the national and European level is based on its interconnection with the various existing platforms and equipment at the IPHC (preclinical molecular imaging, proteomics based on mass spectrometry analysis, cell and molecular biology laboratory, pet shop, and animal physiology and behavior laboratory) making a unique place for the development of multiparametric and macroscopic studies of tumor evolution in vitro and in vivo in small animals. The development of one or several beamlines is foreseen. The first beamline will deliver macro beams of 1 to 2 cm diameter at intensities up to 100 nA. To design and define the optical elements mandatory to transport beam efficiently through this beamline, the proton beam delivered from the cyclotron has to be accurately characterized. Along this line, the transverse beam emittance is a parameter of paramount importance. Several techniques of emittance measurements are known and have been successfully tested in the past, e.g. techniques based on foil irradiation [2, 3]. This paper presents three different techniques that have been used to determine the transverse emittances of the beam extracted from CYRCé.

2. Quadrupole variation method

The quadrupole variation method, uses the combination of quadrupole(s) together with profilers [4]. In this technique, the emittance value is obtained from the correlation between the beam size and the quadrupole magnetic field in the transformation matrix model. Assuming the following transformation matrix R:

$$R = \begin{pmatrix} R_{11} + KR_{12} & R_{12} \\ R_{21} + KR_{22} & R_{22} \end{pmatrix}$$

and the transfer matrix of the quadrupole Q:

$$Q = \begin{pmatrix} 1 & 0 \\ K & 1 \end{pmatrix}$$

the resultant matrix taking into account the beam parameter is:

$$\begin{aligned} \sigma_{11}(z) =& (\sigma_{11}(z_0)R_{11}^2 + 2\sigma_{12}(z)R_{11}R_{12} + \sigma_{22}(z_0)R_{12}^2) \\ &+ (2R_{11}R_{12}\sigma_{11} + 2R_{12}^2\sigma_{12})K + R_{12}^2\sigma_{11}(z_0)K^2 \end{aligned}$$

A quadrupole scan consists of a set of N beam profile measurements at a fixed distance from the quadrupole magnet, as the quadrupole field strength is varied over a range of values. Plotting each of the beam size with respect to the quadrupole strength gives a parabolic curve from which the emittance and phase space parameters are extracted. From the fitting process of the parabolic curve the following values are determined:

$$\mathrm{A} = \mathrm{R_{12}}^2\sigma_{11}(\mathrm{z_0});$$

$$\text{-2AB=2 } \mathrm{R_{11}}\ \mathrm{R_{12}}\sigma_{11}+2\mathrm{R_{12}}^2\sigma_{12};$$

$$\mathrm{C+AB^2}= \sigma_{11}(\mathrm{z_0})\ \mathrm{R_{11}}^2+2\sigma_{12}(\mathrm{z})\mathrm{R_{11}R_{12}}+ \sigma_{22}(\mathrm{z_0})\mathrm{R_{12}}^2$$

The determination of the A, B, C coefficients allows finding the Twiss parameters β, α and γ and the corresponding transverse emittance [4]. As shown in Fig. 1, the experimental setup consisted of a doublet of quadrupoles (QA, QB) and 2 beam profilers positions (Diag1, Diag2). The beam profiler, a single-wire scanner, was designed and built at the IPHC (Fig. 2). It consists of two piezoelectric displacement axes: translation and rotation. Table 1 presents the characteristics of the positioning. The wire, made of tungsten, has a thickness of 0.5 mm and is fixed to a Teflon support. The beam deposits its charge on the wire and the current is measured (orders of pA minimum) using a Keithley

Table 1: characteristics of the scanning wire.

Travel	$\pm$ 20.05 (41) mm
Step width	1 - 1.500 nm
Scan range	$\geq$ 1.5 μm
Scan resolution	$\leq$ 1 nm
Velocity	$\geq$ 20 mm/s
Max. frequency	18.5 kHz

device [5]. The quadrupoles have an aperture of $\pm$39 mm, a maximum field gradient of 9.3 T/m and a magnetic length of 297 mm each. The doublet was positioned at a distance of 154.5 mm from the switching dipole (Dip1) located just after the exit of the cyclotron. Profilers were located at 570 mm and 1690 mm away from the center of the doublet. The polarity of each of the quadrupoles was reversed during the tests, which gave a total number of 8 sets of values while varying the field gradients. Measurements were performed for protons at kinetic energies of 25 MeV and at a constant beam intensity of 25 nA.

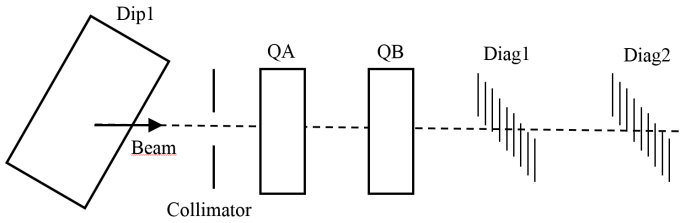

Figure 1: Schematic view of the quadrupole variation method and the different optical elements for the emittance measurement. Dip1 is the dipole at the exit of the cyclotron, QA and QB are quadrupoles, Diag1 and Diag2 are the profiler's positions.

The intensity of the beam was measured as a function of the current in the coils of the quadrupoles QA or/and QB. The main objective was to find the set up values in each configuration which gives a waist to the beam at the profilers location. Fig. 3 shows the variation of the particle density according to the quadrupole fields at a proton energy of 25 MeV. In this example, QA was

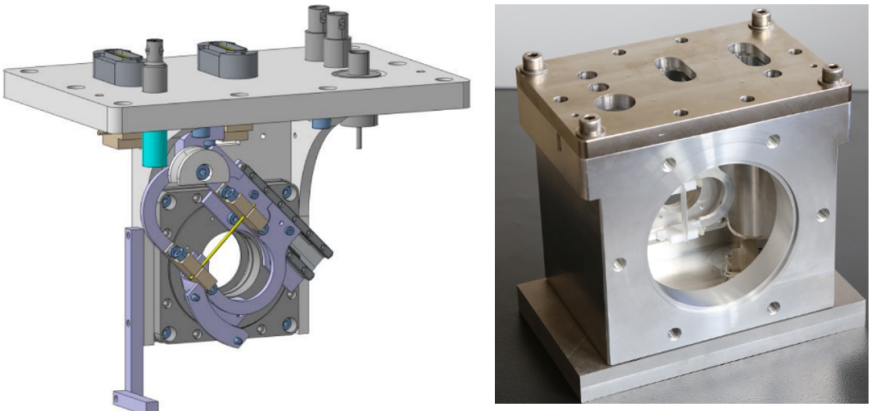

Figure 2: 3D view (left) and picture (right) of the single-wire scanner.

focussing in the x axis and QB in the y axis.

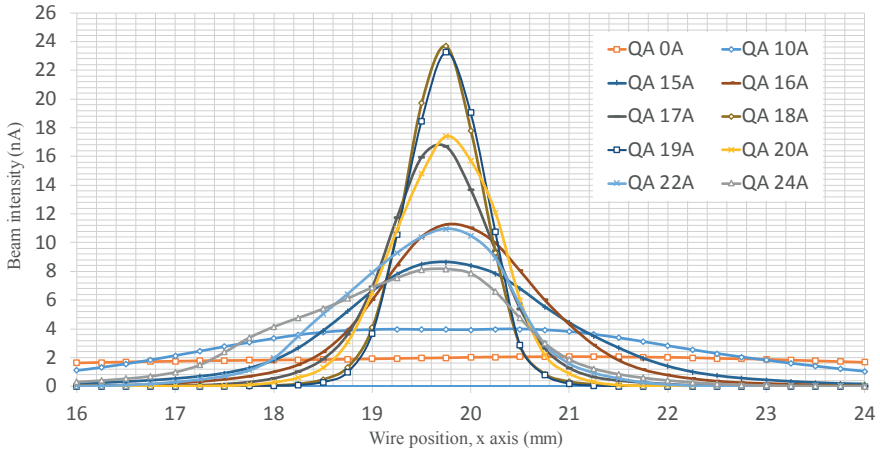

Figure 3: Beam intensities measured on the first profiler (Diag1) according to the intensity in the coils of the quadrupoles QA. I(QB) = 0A. Proton at 25 MeV. Beam waist measured when I(QA)=18A.

From the quadratic functions (Fig. 4), the emittance-related coefficients were calculated. Some difficulties with beam alignment and centering at the quadrupole positions were encountered during the measurements influencing the results. Therefore, several combinations of dipole settings and foil positions were used during the measurements. Moreover multiple peak structures were

observed in the horizontal profiles contributing to large uncertainties in the estimated values. The origin of the latter is considered to be associated with beam extraction from multiple orbits in the cyclotron. The emittances were mesasured to be:

$\epsilon_x{}^{rms}$= 1.9 ± 1.3 π·mm·mrad and $\epsilon_y{}^{rms}$= 3.7 ± 1.4 π·mm·mrad.

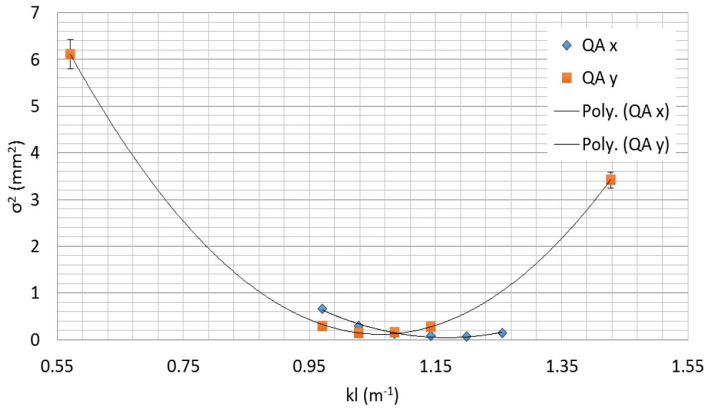

Figure 4: Beam size values according to the strength of the quadrupole QA (Diag1), 25 MeV.

3. Method based on a slit and a beam profiler

The trasverse beam emittance was also assessed by using a movable slit and a single wire position scanner profiler. Fig. 5 shows the principle of this method. The angle x_0 is determined with a multi-wire harp profiler. In the field-free drift space the trajectories of the particles, combined in a 'beamlet', are straight lines. The contribution to the emittance plot in the phase space is given by the angle distribution at the slit location. The slit position is then scanned through the beam to get all positions. The data have to be normalized to a constant beam current as measured. After making the full scan, the X-X' ellipse is plotted and the rms-value of the emittance is calculated from the data. The resolution for the space coordinate Δx is limited by the slit width $\Delta x = d_{slit}$.

The harp profiler consisted of two frames with 48 Tunsten wires with a thickness of 150 μm each ($2r_{wire}$), installed in a flat feedthrough on the rod of

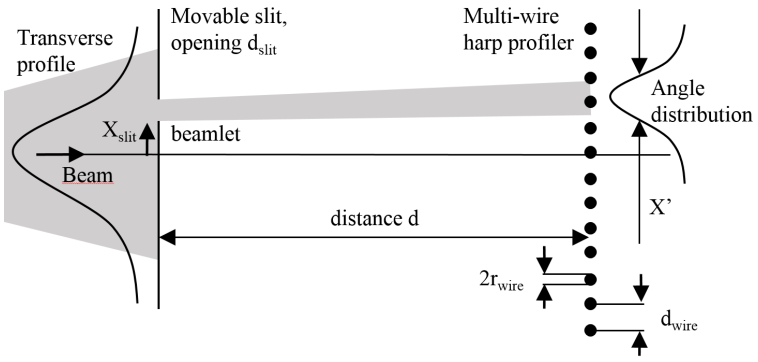

Figure 5: Moving slit technique. The width of the slit d_{slit} gives the resolution in space $\Delta x = d_{slit}$ and the angular resolution is $\Delta x\prime = (d_{slit} + 2\ r_{wire})/d$.

pneumatic actuator with a long strocke of 300 mm (Fig. 6). The drive design allows precise alignment of the detector with respect to the beam axis. The entire mechanical system was assembled on a mounting flange.

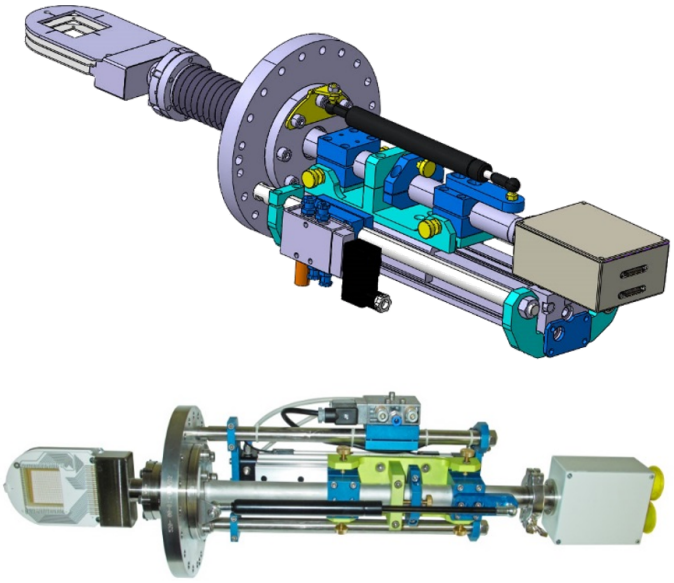

Figure 6: 3D view (top) and picture (bottom) of the multi-wire profiler.

The measurement of the signal from the wire is done by integrating the

charge over a certain period of time. Varying the integration time allows changing the dynamic range of the profilometer over a wide range and choosing the most optimal value based on the beam parameters. The integration time can be set from 1 ms to several seconds. To collect the charge on each wire, 0.2 nF capacitors are used. The average current on the wire is determined by the value of the voltage on the capacitor. The main electronics module used includes two sections of 48 channels each, a power supply with an output voltage of 15 volts and an additional unit with a voltage of 100 volts to power the collecting electrodes. The data set interface allowed to visualize the measured vertical and horizontal beam profiles, as well as the values of their center of gravity and width.

The distance between the wires, d_{wire}, was 1 mm. The size of the slit, d_{slit}, was 200 μm. For the measurement, the doublet was kept positioned at a distance of 154.5 mm from the switching dipole located just after the exit of the cyclotron. The profiler was set a distance of 169 mm away from the doublet of quadrupoles. The angular resolution of the system, defined by $\Delta x\prime=(d_{slit}+2\ r_{wire})/d$, was 0.30 mrad.

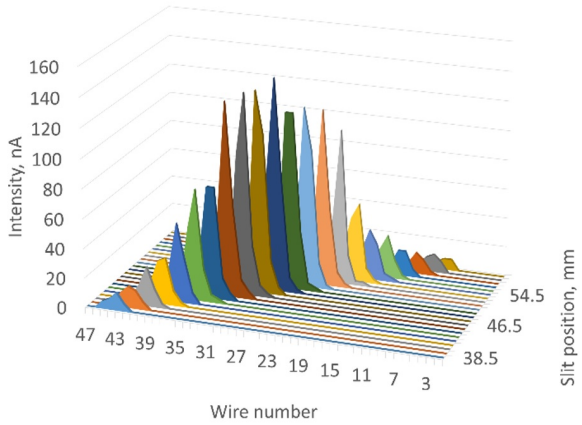

Figure 7: Intensity measured on the wires of the grid (vertical position) for proton energy of 25 MeV. Figure in colour

Fig. 7 shows an example of the set of data measured while the slit is in

the vertical position. The intensity of the beam was kept constant at 120 nA during the measurement process. An additional estimation of the transverse emittances was performed by using TraceWin [6] in order to verify the results obtained by the slit-and-grid method. Indeed, the beam distributions were reproduced in the code and the input beam parameters used in the simulations were adjusted to achieve matching between the simulated and the measured profiles. This allowed to make an estimation both of the emittances and the upstream beam parameters (after the dipole). Fig. 8 and 9 show the beam output distributions implemented in Tracewin from the experimental data at the profiler location and the distributions simulated with TraceWin respectively. From these analyses, transverse emittance was estimated at 25 MeV:
$\epsilon_x{}^{rms}$= 1.4 ± 0.2 π·mm·mrad and $\epsilon_y{}^{rms}$= 5.4 ± 0.2 π·mm·mrad.

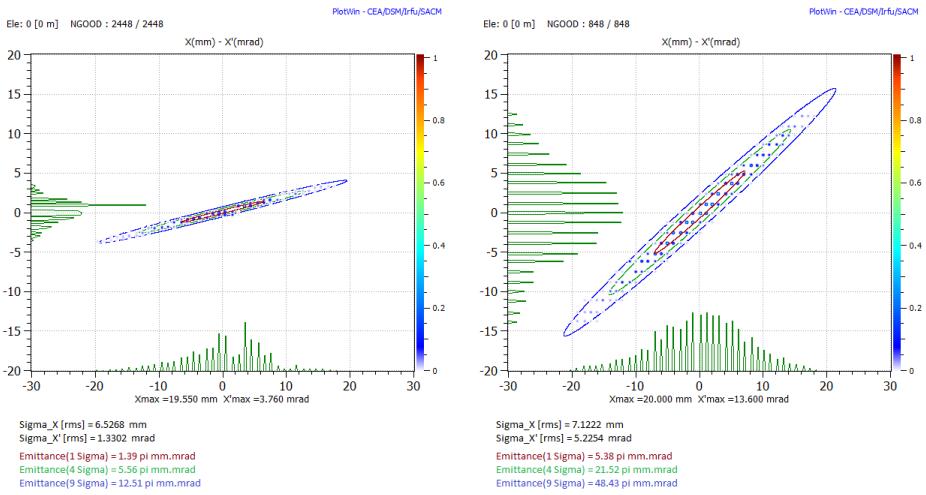

Figure 8: Beam output phase-space distribution in xx' and yy' from experimental data. Figure in colour.

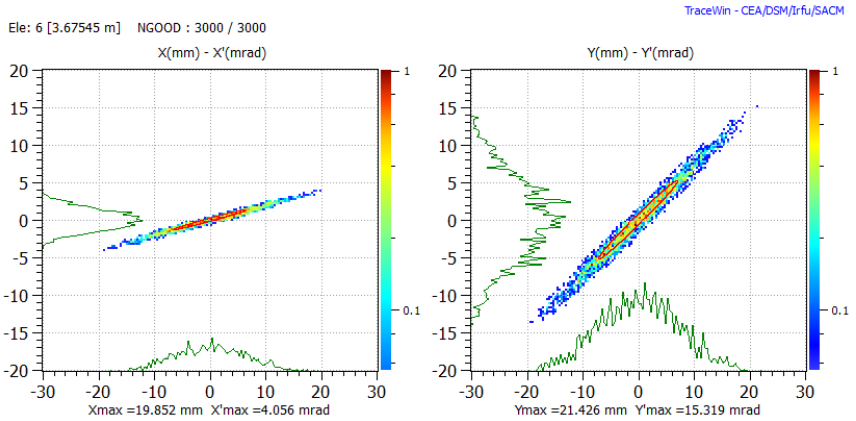

Figure 9: Beam output phase-space distribution in xx' and yy' from simulation. Figure in colour.

4. Multiple beam profiler technique

A system for online measurement of the transverse beam emittance has been developed at the AEC-LHEP of the University of Bern and is described in [7]. The system, named ^{4}PrOBεaM, consists of four UniBEaM beam monitors, also conceived and built at AEC-LHEP [8, 9]. The UniBEaM detector is based on a single scintillating fiber moved across the beam. When a charged particle passes through the fiber, light is produced and transported through a standard multi-mode optical fiber to a read-out device. There the signal is digitized and plotted online as a function of the fiber position. The signal measured by the UniBEaM profiler is linear with respect to the beam current over a wide range from 1 pA to about 3 μA [8].

The ^{4}PrOBεaM system allows the transverse beam emittance to be measured in each plane in a fraction of a minute. It uses the multipole beam profiler method [10]. Beam profiles are measured at four locations along a beamline, as shown in Fig. 10. For each of them, the variance (RMS^2) and its uncertainty are calculated giving an estimate of $\sigma_{11}(s)$ component of the beam matrix $\sigma(s)$ at the location s, as depicted in Fig. 11. The beam transfer matrix $R(s)$ involves

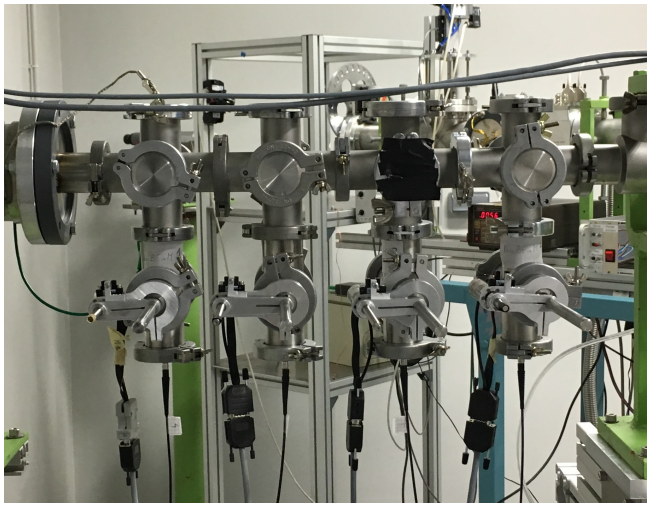

Figure 10: The ^{4}PrOBεaM system installed on the research beamline of the TR24 cyclotron in Strasbourg. Four UniBEaM beam profilers are visible.

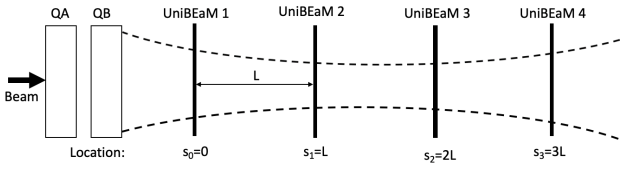

Figure 11: Sketch of principle of the multiple beam profiler method for the measurement of the transverse beam emittance.

only a drift:

$$R(s) = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix}$$

The beam matrix at any location s with respect to the location of the first profiler ($s_0 = 0$) is therefore given by the formula:

$$\sigma(s) = R(s)\sigma(0)R(s)^T$$

From the equation above it can be derived that $\sigma_{11}(s)$ is a quadratic function

of s:

$$\begin{aligned}\sigma_{11}(s) &= \sigma_{22}(0)s^2 + 2s\sigma_{12}(0) + \sigma_{11}(0) \\ &= f(s; \sigma_{11}(0), \sigma_{12}(0), \sigma_{22}(0)),\end{aligned}$$

where $\sigma_{11}(0)$, $\sigma_{12}(0)$, and $\sigma_{22}(0)$ are the components of the $\sigma(0)$ matrix. These components and consequently the transverse RMS emittance $\epsilon^{rms} = \pi\sqrt{\det(\sigma(0))}$ are evaluated by fitting the $f(s; \sigma_{11}(0), \sigma_{12}(0), \sigma_{22}(0))$ function using the four data points representing the estimated variance values as a function of the location s, as shown in Fig. 12.

The emittance measurements of the TR24 cyclotron in Strasbourg were conducted at the research beamline. The beam current of 10 nA was kept throughout the measurements and was monitored by means of a Faraday cup installed at the end of the beamline. The RMS transverse beam emittance was evaluated in both the horizontal and vertical planes at the two most frequently used beam energies of 18 MeV and 25 MeV. Proton beams resulting from the TR24 cyclotron are produced by stripping accelerated H^- ions. The stripper angle can be adjusted to optimize the extracted proton beams. For each beam energy, measurements were repeated for different stripper positions to evaluate the sensitivity of the emittance to changes of the stripper azimuthal angle.

The results of the emittance measurements for different stripper positions are shown in Figs. 13 and 14 for beam energies of 18 MeV and 25 MeV respectively. The stripper positions chosen are those which are used most often at IPHC and are given by a numerical parameter. For 18 MeV protons, the horizontal emittance was found to be in the range of (5.01 ± 0.28) π·mm·mrad to (5.81 ± 0.48) π·mm·mrad. The vertical emittance varied from (5.04 ± 0.17) π·mm·mrad to (6.94±0.19) π·mm·mrad. For 25 MeV protons, the dependence on the stripper position is weaker. This, however, could be due to the different range in which the stripper angle was changed. In the horizontal plane, the emittance varied from (2.79 ± 0.21) π·mm·mrad to (3.03 ± 0.22) π·mm·mrad, while in the vertical one from (5.76 ± 0.18) π·mm·mrad to (5.96 ± 0.16) π·mm·mrad.

The measured value of the vertical RMS beam emittance was always larger

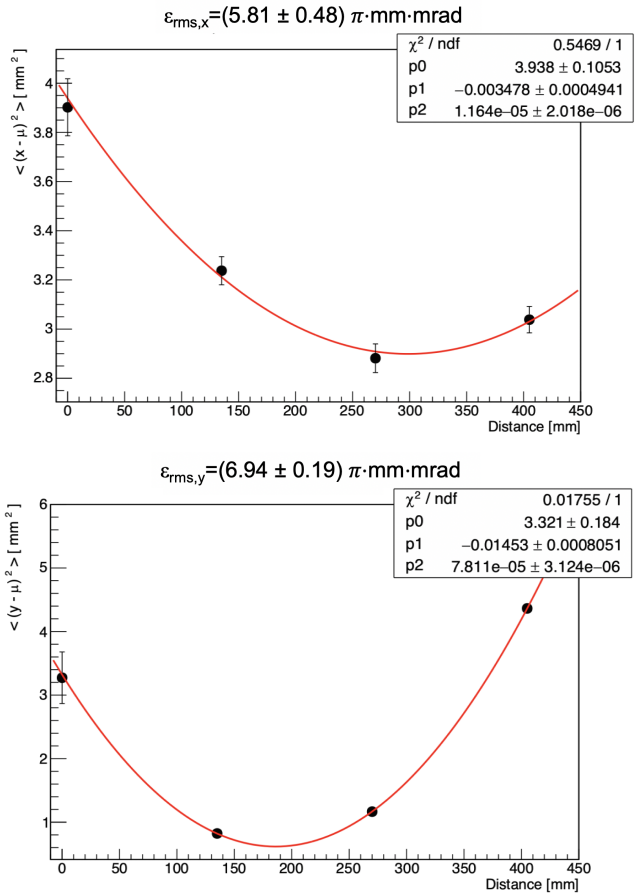

Figure 12: Variance of transverse beam profiles as a function of the location obtained for the horizontal (top) and vertical (bottom) planes.

than the corresponding value of the horizontal one. This is probably due to the axial injection of H^- ions from the external ion source. Acceleration from the injection point to the extraction stripper is realized in the horizontal plane, and therefore the axially injected ions must be deflected by 90 degrees, which leads to emittance growth in the vertical plane.

In conclusion, the upper limits of the beam emittance for the 18 MeV proton beam were found to be (5.81 ± 0.48) π·mm·mrad and (6.94 ± 0.19) π·mm·mrad for the horizontal and vertical planes, respectively.

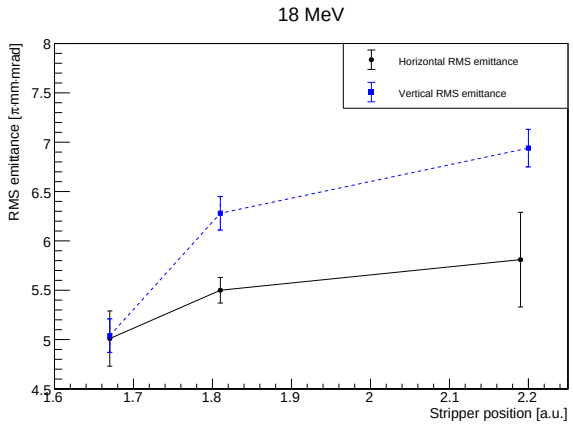

Figure 13: The RMS transverse beam emittance of the 18 MeV proton beam of the TR24 Strasbourg cyclotron as a function of stripper angular position.

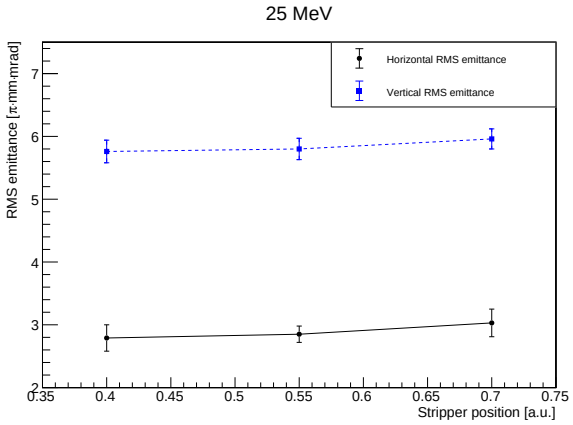

Figure 14: The RMS transverse beam emittance of the 25 MeV proton beam of the TR24 Strasbourg cyclotron as a function of stripper angular position.

5. Conclusions

The measurement of the transverse emittance of the beam extracted from the CYRCé TR24 cyclotron is challenging due to many parameters influencing its value. Therefore, only some ranges of values and upper limits can be provided to design the new beamline. Three different methods were used. Overall results agreed that the vertical transverse emittance was at least twice as

Table 2: RMS values of the transverse emittances (in mm.mrad) according to the method used and the beam energy (in MeV).

Method	ϵ_x	$\Delta\epsilon_x$	ϵ_y	$\Delta\epsilon_y$	Energy
Quad scan	1.90	1.30	3.70	1.40	25
Slit and grid	1.40	0.20	5.40	0.20	25
Multiple profilers	3.03	0.22	5.96	0.16	25
Multiple profilers	5.81	0.48	6.94	0.19	18

large as the horizontal one at a proton energy of 25 MeV (Table 2). The horizontal emittance is between ${\epsilon_x}^{rms}$= 1.40 ± 0.20 π·mm·mrad and ${\epsilon_x}^{rms}$= 3.03 ± 0.22 π·mm·mrad. The vertical emittance is between ${\epsilon_y}^{rms}$= 3.70 ± 1.40 π·mm·mrad and ${\epsilon_y}^{rms}$= 5.96 ± 0.16 π·mm·mrad. The third method also allowed to estimate upper limits of the transverse emittance at proton energy of 18 MeV: ${\epsilon_x}^{rms}\leq$ 5.81 ± 0.48 π·mm·mrad and ${\epsilon_y}^{rms}\leq$ 6.94 ± 0.19 π·mm·mrad.

The variance of the results from the different measurements originates from the accuracy of the methods, various misalignments and offsets (beam, magnets) and cyclotron related (extraction from multiple orbits, cyclotron oscillations etc.). Nevertheless, these measurements allowed to start the design of the new beam line for radiobology irradiations and to define the optical elements that will be needed to compose it.

References

[1] ACSI website available at: `http://www.advancedcyclotron.com/` (accessed on March 29th, 2019).

[2] C. Tamburella, T. Giles, Beam diagnostics for an 18 MeV medical cyclotron, NIM B 266 (2008) 4678.

[3] A. Degiovanni et al., Emittance Measurements at the Strasbourg TR24 Cyclotron for the Addition of a 65 MeV Linac Booster, Proceedings of Cyclotrons (2013) 329–331.

[4] H. Wiedemann, Particle Acelerator Physics, Springer 3rd Edition.

[5] Keithley Series 6400 Picoammters, available at:
https://www.tek.192 com/193 keithley-series-6400-picoammeters (accessed on March 29th, 2019).

[6] D. Uriot et al., TraceWin Documentation, available at:
`http://irfu.cea.fr/Sacm/logiciels/index3.php` (accessed on March 29th, 2019).

[7] K. P. Nesteruk et al., A system for online beam emittance measurements and proton beam characterization, JINST 13 (2018) P01011, arXiv:1705.07486.

[8] M. Auger et al., A detector based on silica fibers for ion beam monitoring in a wide current range, JINST 11 (2016) P03027.

[9] D. E. Potkins, S. Braccini, K. P. Nesteruk, T. S. Carzaniga, A. Vedda, N. Chiodini, J. Timmermans, S. Melanson, M. P. Dehnel, A Low-cost Beam Profiler Based On Cerium-doped Silica Fibers, Physics Procedia 90 (2017) 215 – 222, conference on the Application of Accelerators in Research and Industry, CAARI 2016, 30 October - 4 November 2016, Ft. Worth, TX, USA.

[10] K. T. McDonald, D. P. Russell, Methods of emittance measurement, Month M., Turner S. (eds) Frontiers of Particle Beams; Observation, Diagnosis and Correction. Lecture Notes in Physics, Springer 343.