

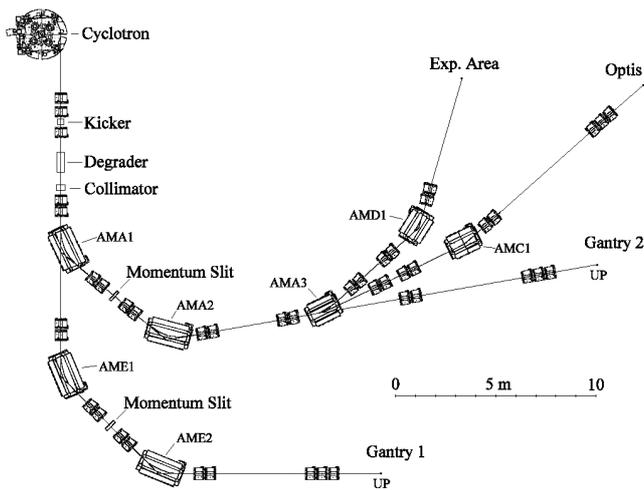
# OPTICAL DESIGN OF THE PROTON BEAM LINES FOR THE PROSCAN PROJECT

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The optical design for the final layout of the beam lines for the PROSCAN project is presented here. Optical computations were mainly done in 1<sup>st</sup> order for the basic design and additionally up to 3<sup>rd</sup> order to study also the influence of contributions to the beam due to chromatic aberrations. Similar work for the design of the Gantries and the Optis apparatus is done by ASM and covered by contributions elsewhere.

## INTRODUCTION

Since 1999 design studies have been under way for finding a location in the former NA-hall to place the new 250 MeV Proscan cyclotron (COMET). It has to deliver its produced proton beam to an already existing and 3 new areas for biomedical applications (and PIF). Some of the many different preliminary versions are shown in references [1] and [2]. A simplified view of the Proscan beam lines for today's practically finalized floor plan layout is shown in Fig. 1. Only the most important components like cyclotron, kicker magnet, degrader, collimator, momentum slits, 7 bending magnets, 44 quadrupole lenses, meeting points (UP) and beam axes are drawn.



**Fig. 1:** Floor plan layout of the 4 Proscan beam lines to Gantry1, Gantry2, Optis and the Experimental Area. Included are only the main optical components.

## DIVISION IN GROUPS

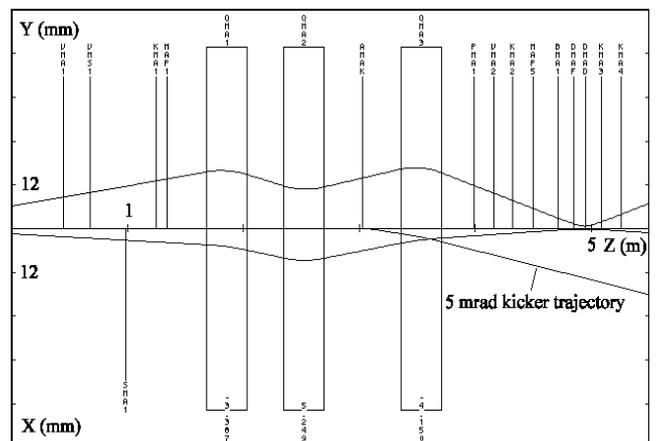
The optical design of the beam lines may best be done by dividing the problem into 5 different sections:

- (1) cyclotron exit → degrader (Fig. 2)
- (2) degrader → UP of Gantry 1 (Fig. 3)
- (3) degrader → UP of Gantry 2
- (4) degrader → Optis area (UP not yet defined)
- (5) degrader → experimental area (e.g. for PIF).

Since the space for this article is limited, only sections 1 and 2 will be discussed here in more details. Because the same criteria were applied for all cases, the optical design for sections 3 to 5 look pretty similar to the one for section 2, which will be discussed here in more details.

## COMMON SECTION WITH DEGRADER

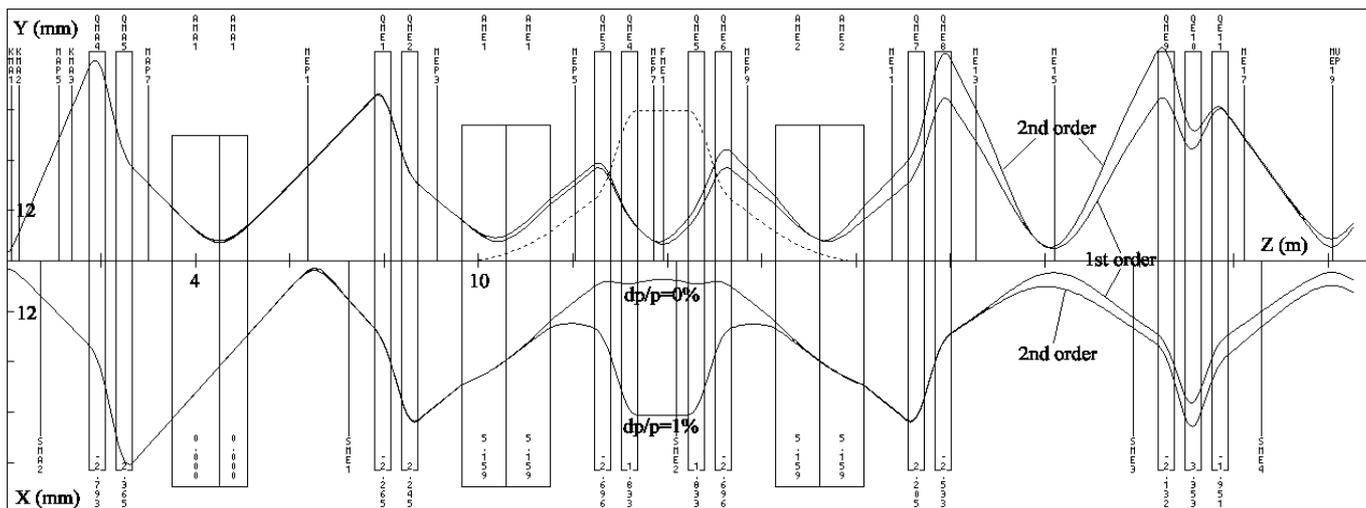
Results of TRANSPORT [4] calculations done for beam line section 1 are shown in Fig 2. With the first Q-triplet after the cyclotron, a beam spot as small as possible is produced at the degrader consisting of high-density ( $\rho=1.88 \text{ g/cm}^3$ ) graphite wedges [3]. In order to get a round spot at the degrader – which is desirable – the projected emittances in x and y have to be equal within about a factor of 2 (not yet the case with the latest cyclotron model calculations done by Accel, see Fig. 2). A fast kicker magnet (5 mrad horizontal deflection-angle) for on/off-switching the beam on user request (within 100  $\mu\text{s}$ ) is mounted between the 2<sup>nd</sup> and 3<sup>rd</sup> quadrupole lens. Because the 3<sup>rd</sup> lens is horizontally defocusing, the deflection of the centroid is amplified by a factor of 1.5, which results in a horizontal beam deviation from the axis of about 12 mm at the stopper located near the entrance of the degrader box [3]. First Monte-Carlo simulations with the computer code TURTLE [5] show that under ideal conditions beam suppression ratios down to  $10^{-5}$  should be reachable with the kicker.



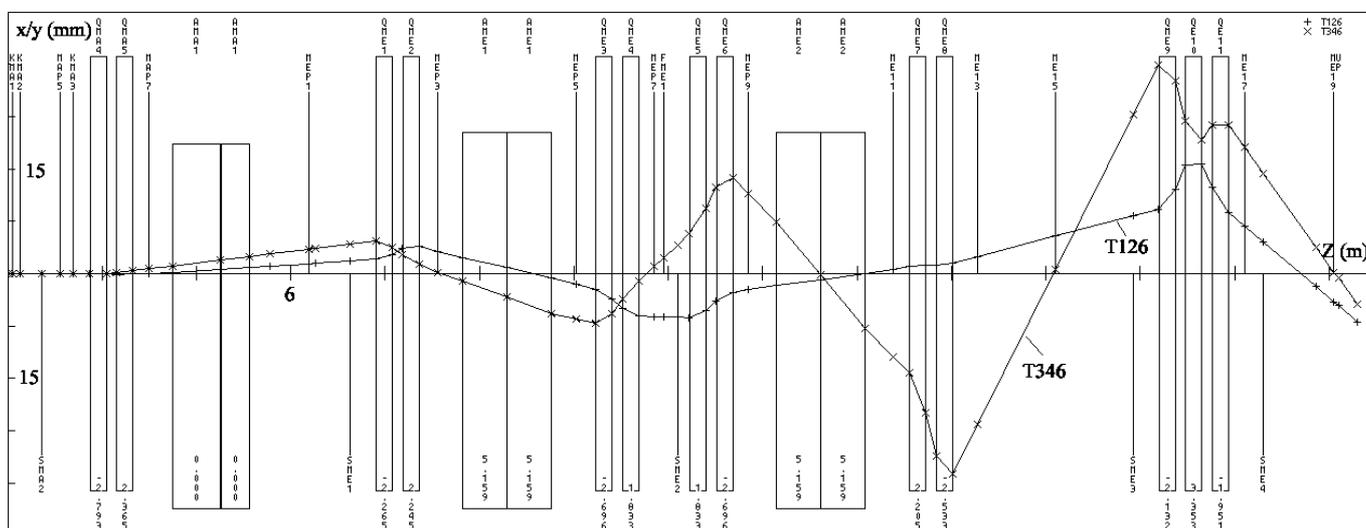
**Fig. 2:** First order  $2\sigma$ -envelopes of the beam starting at the cyclotron exit and going through the first Q-triplet to the degrader together with the central trajectory of the beam horizontally deflected by the kicker magnet. The used values of the projected emittances  $\epsilon_x=0.65\pi \text{ mmmrad}$  and  $\epsilon_y=10.3\pi \text{ mmmrad}$  are from preliminary data delivered by Accel (manufacturing company of the 250 MeV cyclotron).

## BEAM LINE TO GANTRY 1

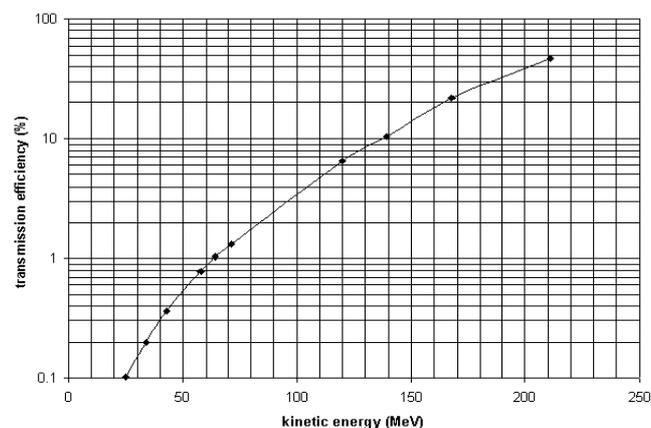
Fig. 3 shows the 1<sup>st</sup> and 2<sup>nd</sup> order Transport envelopes of the optics for the beam line section between the virtual waist in the degrader and the meeting point of Gantry 1 (UP).



**Fig. 3:** First and second order envelopes of the 70 MeV-optics for the beam line between the degrader and the meeting point of the existing Gantry 1. The dotted line is the 1%-dispersion trajectory. At the dispersive focus both envelopes for  $dp/p=0\%$  and  $1\%$  are drawn. The second order contributions are mainly caused by the chromatic aberration-coefficients T126 and T346 (see Fig. 4).

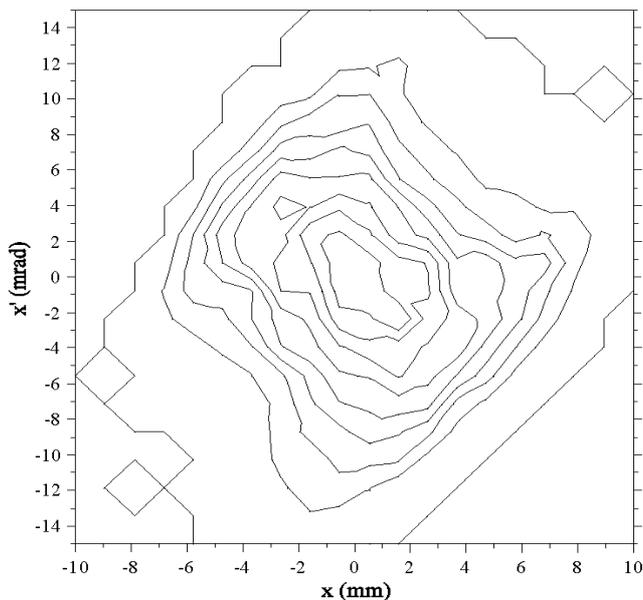


**Fig. 4:** The 2 beam-contributions from the 2<sup>nd</sup> order chromatic aberration-coefficients T126 and T346. (In this graphic display the contribution to the envelopes of both coefficients is drawn for  $dp/p=1\%$  and  $x'_0=11.6$  mrad or  $y'_0=26.6$  mrad.)

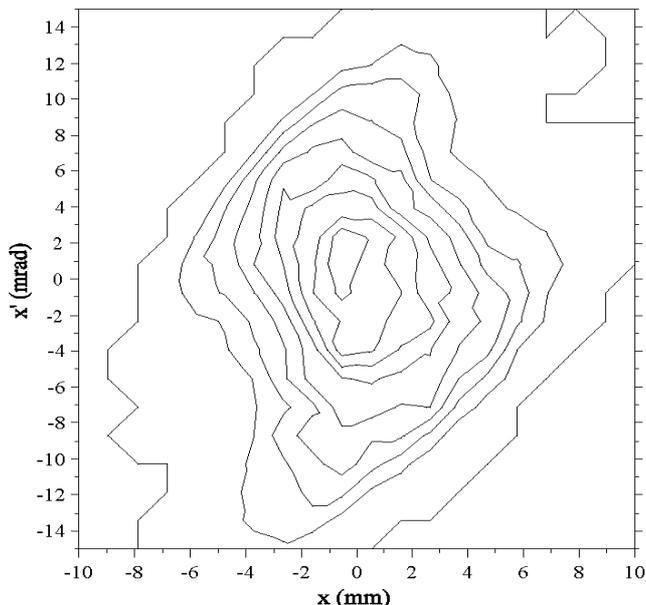


**Fig. 5:** Transmission efficiency of the Proscan beam lines as a function of the kinetic energy. At 70 MeV the value for the transmission is about  $1.3 \pm 0.1\%$ .

As x- and y-starting values 2 mm are used, whereas the x'- and y'-starting values are chosen to display the maximum amplitudes allowed to be inside the quadrupole apertures ( $x'_0=11.6$  mrad and  $y'_0=26.6$  mrad). All of them have an aperture radius of 50 mm and the inside diameters of the vacuum tubes are 90 mm. A vertical waist is placed in all 3 bending magnets so that a gap size of 65 mm is sufficient (inside height of vacuum chamber = 54 mm). Two bending magnets (AME1 and AME2) and 4 symmetrically arranged quadrupoles are needed to deflect the beam by 90 degrees and to keep under control the dispersion and the vertical cosine-trajectory. At the intermediate focus between the 2 Q-duplets the momentum bandwidth may be controlled by a movable slit-collimator. In this region both horizontal envelopes for  $dp/p=0\%$  and  $1\%$  together with the dotted 1%-dispersion trajectory are drawn.



**Fig. 6:**  $x/x'$ -contour diagram of a Monte-Carlo first-order simulation for the 70 MeV beam at the meeting point (UP) for Gantry 1. The RMS-value for  $x$  is 2.9 mm and for  $x'$  4.7 mrad.



**Fig. 7:**  $x/x'$ -contour diagram of a Monte-Carlo third-order simulation for the 70 MeV beam at the meeting point (UP) for Gantry 1. The RMS-value for  $x$  is 2.6 mm and for  $x'$  5.3 mrad.

## HIGHER ORDER EFFECTS

The display of the second half of this beam line section (Fig. 3) shows a well visible difference between the 1<sup>st</sup> and 2<sup>nd</sup> order envelopes. The dominant 2<sup>nd</sup>-order contributions are due to the chromatic aberration-coefficients T126 and T346. These 2 coefficients are graphically displayed in Fig. 4 for a  $dp/p = 1\%$ ,  $x_0' = 11.6$  mrad and  $y_0' = 26.6$  mrad. According to the magnitude of the 2<sup>nd</sup>-order effects at the meeting-point (UP), the beam spot size would almost double compared with the 1<sup>st</sup>-order values, which would require, that some sextupole correcting devices may have to be inserted into the beam line. But a Monte-

Carlo simulation with the computer-code TURTLE [5] shows, that this is not necessary. Fig. 6 and Fig. 7 show the  $x/x'$ -contour-plot at the meeting point UP of Gantry 1. There is almost no significant difference between the plot for 1<sup>st</sup>-order only and the one, which shows the results of computations with contributions of up to 3<sup>rd</sup>-order. This effect has also been observed at PSI's high-acceptance Myon beam lines [6], where tests with the real beam show, that the TRANSPORT 2<sup>nd</sup>-order envelopes are overestimated and that the results of TURTLE computations correspond pretty much to the measured beam spots.

## SPECIAL DEVICES

For the verification of the optics and for centring the proton beam along the beam line, a series of beam scanners (profile monitors) for both directions (in  $x$  and  $y$ ) are required. In Fig. 3 (and Fig. 4) the position of these devices are marked with vertical lines pointing upwards and having labels like MAnn/ME<sub>nn</sub>. The positions of the steering magnets required for centring the beam are marked similarly with vertical lines pointing downwards and having labels like SMAn/SM<sub>En</sub>. All quadrupole lenses are equipped with mirror plates in order to avoid overlapping effects with the fringe fields of the adjacent quadrupoles. This helps to produce good agreements of measured beam envelopes with TRANSPORT predictions, because the effective lengths of the quadrupoles remain uninfluenced by their actual settings. As may be seen from Fig. 3 and Fig. 9 some beam losses will occur at all quadrupoles. Therefore after each Q-duplet and Q-triplet a 4-segment halo monitor will be placed to gather some info about the beam spill for an online display.

## MEETING POINT CONDITIONS

Fig. 7 gives also the  $1\sigma$ -values of  $x$  and  $x'$  at the meeting point UP of Gantry 1. Since a Q-triplet is used in front of the meeting point (UP), it is possible to tune its settings in such a way, that a 'round' ( $x=y$ ) spot at the UP may be achieved. Thus, for the reason of a good matching with the Gantry 1 optics at UP [2], the  $2\sigma$ -values of the projected emittance at the double-waist listed below are met.

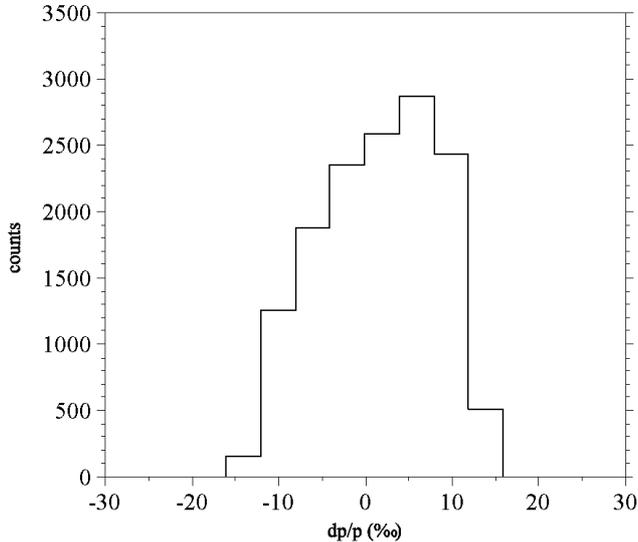
$$x \approx y \approx 6 \text{ mm} \quad \text{and} \quad x' \approx y' \approx 10 \text{ mrad}$$

Because for the three other beam line sections similar optical device blocks are used, no significant differences in the optical design are apparent and worthwhile to be mentioned or shown in this article.

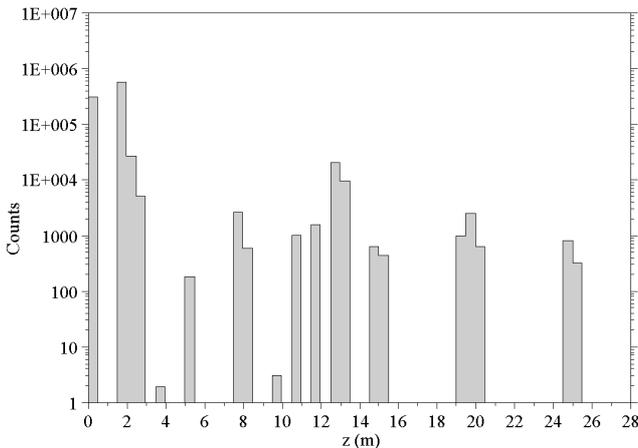
## TRANSMISSION EFFICIENCY

The transmission efficiency of the beam lines to the Gantries and the Optics and Experimental areas is strongly dependent on the chosen kinetic energy of the protons (see Fig. 5). This is due to the fact, that the energy and angular straggling of the degrader material with variable thickness are producing a phase space more or less larger than the phase space acceptance of the beam lines. The  $dp/p$ -distribution of

the accepted and transmitted protons is shown in Fig. 8. Its width is about  $\pm 1.2\%$ , which is given by the dispersion trajectory between AME1 and AME2 and the aperture size there (see Fig. 3). This maximum value is considered to be sufficient for the production of a smooth SOBP (Spread-Out-Bragg-Peak) with not too many energy steps [2].



**Fig. 8:** Momentum transmission distribution of the Proscan beam lines (at 70 MeV). The RMS-value is about 0.68%.



**Fig. 9:** Result of a Monte-Carlo simulation (3<sup>rd</sup> order) of the losses for protons along the beam line between the degrader ( $z = 0$  m) and the meeting point (UP at  $z \approx 28$  m) of Gantry 1 for  $E = 70$  MeV beam-settings. The location of the components along  $z$  may be seen from Fig. 4.

## BEAM LOSSES

For almost all energies used for proton therapy the degrader has to be used. Therefore the full aperture of all quadrupoles after the degrader will be filled with some beam, which has the consequence, that at each Q-duplet or Q-triplet some protons will be lost. Fig. 9 shows a typical loss diagram (computed with the Monte-Carlo program TURTLE [5]) along the beam line from the degrader to the Gantry 1 meeting point with a longitudinal resolution of 0.5 m. The used model is simplified by only applying multiple scattering

at the degrader and not at the following aperture constraints. In reality the losses will be more smeared out. In this example the degrader was set for degrading the proton beam from 250 down to 70 MeV (kinetic energy) and the number of tracked particles was  $10^6$  protons. Most of them (95 %) are lost at the degrader and the following ( $x'/y'$ )-definition-slit in front of the 1<sup>st</sup> Q-duplet. Therefore, starting at the degrader the first 3 to 4 meters of the beam line are becoming the most activated region of the PROSCAN beam lines. Some local shielding for the components here has to be foreseen. The sum of the lost protons along the whole beam line at 70 MeV is 98.5 % in a 1<sup>st</sup>-order run and 0.06 % higher in a 3<sup>rd</sup>-order run, since there are slightly more protons with exceeding amplitude in the last Q-duplet and Q-triplet (see Fig. 3).

## FINAL REMARKS

If the reader would like to learn more about the PROSCAN beam lines in a wider context, then the review document "Architectural overview of the PROSCAN beam lines" compiled by M. Schippers [7] is recommended to be looked at. To further confirm the claim, that higher order aberrations are not influencing the beam transport substantially, it is planned to study the optical behaviour of the current layout also with the computer code COSY INFINITY [8].

## REFERENCES

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