# PERFORMANCE TESTS OF THE DEGRADER DRIVE OF THE PROSCAN FACILITY 

H. Reist, T. Böhringer, V. Ovinnikov, P. Rüttimann, C. Zumbach


#### Abstract

The performance tests demonstrated the fulfilment of the specifications for the application of the spot scan technique and for the implementation of energy modulation in lateral scanning. They include examination of the manufacturing accuracy and of the operation with respect to the specified design, reliability and availability of the scheduled beam time. The examination of the degrader drive includes the control of the calibration procedures provided for the daily or weekly tests, the measurements of the accuracy of the switching positions of the inner and outer end switches and the assessment of the linearity, accuracy, reproducibility and speed of positional changes for the energy settings between 238 and 70 MeV .


## INTRODUCTION

Proton therapy with the COMET cyclotron, which delivers beam at the fixed energy of 250 MeV , needs a degrader assembly to adjust the energy of the proton beam from 250 MeV down to $\sim 70 \mathrm{MeV}$ for the application of the depth dose. This is accomplished by using two multi-wedge high-density graphite absorbers that allow continuous adjustment of the beam energy by moving into the beam simultaneously and from opposite sides. Advanced radiation techniques place high demands, not only on the operation of the degrader assembly with regard to the specified design, but also on the reliability as well as the availability of the scheduled beam time.

A first set of performance tests concerned the measurement of the water equivalent thickness of the graphite and the examination of the manufacturing accuracy of the multi-wedge absorbers. It also contained checks of the operation with respect to the specified design, the inspection of the accuracy, linearity, reproducibility and of the speed of positional changes of the degrader drives for the energy settings within the adjustable range between 238 and 70 MeV .

A further set of checks included the calibration procedures provided for the daily or weekly tests. This applies to the measurement of the positions of the switching points of the inner and outer end switches relative to the sidewall of the vacuum chamber of the degrader unit. It pertains to the determination of the distance between them in terms of mm and in terms of the number of motor steps it takes to move from one switching point to the other. Additional checks concerned the accuracy of the switching positions and the spread of the counted number of the necessary motor steps for given positional changes of the drives.
Another set of tests referred to the reliability, availability of the scheduled beam time and to short beam interruption periods for service and repair work. They comprehended the check of the temperature rise of the multi-wedge absorbers under maximum beam load, which is equivalent to a 90 Watt heat load, with and without water cooling.

The vacuum pump-down time after venting was also recorded. This is an important factor for the availability.
An important part of the testing applied to the tools designed to assist in the mounting and demounting of
the components of the degrader unit. It was essential to train the maintenance staff in the mounting and demounting of the components in consideration of easiness, safeness, length of time and of an optimal use of the lead shield to minimise the dose load.

## EXAMINATION OF THE OPERATION PERFORMANCE OF THE DEGRADER DRIVE

Table 1 contains a selection of specifications of the degrader drive that serve as a reference for the subsequently characterised tests.

| Parameter | Specifications |
| :--- | :--- |
| Energy range | continuously variable <br> between $238-70 \mathrm{MeV}$ |
| Typical unit interval of <br> energy variation and <br> step length of the drives | $\Delta \mathrm{E}$ equivalent to 4.5 mm <br> water corresponds to a <br> step length of 1.176 mm |
| Uniformity within an area <br> of 15 mm diameter | $\pm 0.025 \mathrm{~mm}$ thickness <br> tolerance of the graphite <br> absorber |
| Accuracy, linearity and <br> reproducibility of <br> positional changes of the <br> drives | $\pm 0.025 \mathrm{~mm}$ |
| Response time of <br> positional changes | 1.176 mm within 50 ms |

Table 1: Specifications applying to the degrader drives.

## Examination of the water-equivalent thickness of the graphite absorber

An accurate calibration of the water-equivalent thickness of the graphite absorber is indispensable for the dimensioning of the multi-wedge absorbers. The type of graphite used, R6710 from SLG Carbon, is a high-density graphite of $\rho=1.88 \mathrm{gcm}^{-3}$, with a suitable heat conductivity of $\lambda=100 \mathrm{Wm}^{-1} \mathrm{~K}^{-1}$ and good mechanical properties. The water equivalent thickness was determined from the differences of Bragg-peak distributions that were measured with and without graphite plates at the existing therapy gantry 1 with 160 MeV protons. The setup consisted of the dailycheck phantom using the range-shifter scan and the operation control file "Rangescan_1602_CTO_daily". A Binz ionisation chamber of 8 cm diameter was used to measure the beam current. Five range scans with $0,3,6,8$ and 10 layers of 25 mm thick, accurately
grounded graphite plates, respectively yielded an average water-equivalent thickness that compares well with the calculation:
measured: $\quad R_{\text {H2O }} / R_{\mathrm{C}_{\text {_ }} 1.88 \mathrm{~g} / \mathrm{cm} 3}=1.682 \pm 0.005 \mathrm{~cm}$
calculated: $\quad R_{\mathrm{H} 2 \mathrm{O}} / \mathrm{R}_{\mathrm{C}_{-} 1.88 \mathrm{~g} / \mathrm{cm} 3}=1.689 \pm 0.004 \mathrm{~cm}$.

## Linearity and reproducibility of positional changes of the degrader drives

The examination subdivides into two parts; (i) check of consecutively set positions of the drives with a lasermeasuring device that allows positional measurements with an accuracy of a few microns, and (ii) checks executed with the degrader unit installed in the beam line, including the control system.


Fig. 1: Frequency of the step lengths, which were consecutively set across the operation range of the drives. The positions have been measured with the laser-measuring device. The upper and lower figures show the distributions for step lengths of 10 mm and 0.045 mm , respectively.

The measured length of the 10 mm steps average out to $9.995 \pm 0.006 \mathrm{~mm}$ and the mean value of the 0.045 mm steps is $0.045 \pm 0.003 \mathrm{~mm}$. The checks verified the compliance with the required integral and differential linearity of the positional changes of the degrader drives.

In operation, the voltage readings of the potentiometers specify the positions of the drives. The distribution of the potentiometer readings, which correspond to given step lengths, for example step lengths of 10 and 0.045 mm , revealed two or three peaks and spread asymmetrically beyond the specified limit of $\pm 25 \mu \mathrm{~m}$. A closer examination located
the cause in the pitch of the resistance wire windings of the potentiometers that impairs resolution and differential linearity.


Fig. 2: The figure displays the differences between the potentiometer readings and the linearity-based fit data of successive step lengths of 3 mm across the operation range, from the outer to the inner limit switch. One bit is equivalent to $\sim 4 \mu \mathrm{~m}$.

The average 1-б-error of the data amounts to $\pm 1.2$ bits $(\cong \pm 5 \mu \mathrm{~m})$, and the uncertainty of the start position is $\pm 0.489$ bits ( $\cong \pm 1.94 \mu \mathrm{~m}$ ). The motor step length of $15 \mu \mathrm{~m}$ is equivalent to 3.785 bits. The acceptable deviation from linearity of $\pm 25 \mu \mathrm{~m}$ corresponds to 6.3 bits. The measured deviation from linearity exceeds 15 bits $(65 \mu \mathrm{~m})$. The resolution of the potentiometers is therefore not better than about $65 \mu \mathrm{~m}$ and the linearity is only $\pm 0.25 \%$.
Since the step lengths of the SLO-SYN stepping motors proved to be very stable across the entire operation range, they offer, together with step counters, an alternative means to determine the position within the resolution of the motor step length of $\cong 15 \mu \mathrm{~m}$. This option required replacement of the HONEYWELL limit switches by My-Com F100/S35 precision limit switches, which exhibit switching points within a variation of a few microns. Accurately measured switching points of the outer and inner limit switches define the length of the operation range and provide an absolute calibration of the step counters of the stepping motors and of the potentiometer readings. The calibrated potentiometer readings give an estimation of the position required at start-up or after power failure and allow checks on possible step losses of the step counters. The switching points of the limit switches, measured relative to the sidewall of the degrader vacuum chamber with the lasermeasuring device, amount to $231.425 \pm 0.006 \mathrm{~mm}$ for the switching point of the outer limit switch and $121.673 \pm 0.005 \mathrm{~mm}$ for the inner switching point, respectively. The length of the operation range is given by their difference and is $109.752 \pm 0.011 \mathrm{~mm}$. The statistical errors include both the variations of the switching points of the limit switches and the variation from the laser-measuring device. The examination of the linearity, accuracy and reproducibility of positional changes verified the usability of the position monitoring by the step counters as demonstrated in the following examples.


Fig. 3: The histogram of the counted number of motor steps that it takes to move the drives from the outer to the inner limit switch or in the reversed direction, respectively. The average number of steps amounts to $7326.0 \pm 0.2$.

From the distance between the switches, the average length of a motor step can be calculated as $14.981 \pm 0.002 \mu \mathrm{~m}$, which agrees well with the nominal value of $15 \mu \mathrm{~m}$. The almost non-existent spread of the histogram in Fig. 3 confirms the stability of the average motor step length.
The linearity of the drive has been tested by moving from the outer to the inner limit switch and in the reverse direction, with sequences of given step lengths, which were chosen as $2,3,9,18,407,814$, 2441 and 3662 motor steps, respectively. In order to protect the switches against damage, the control program of the drives makes a halt just in front of the limit switches, and then continues movement by single steps up to the switching points. Fig. 4 exhibits small variations of the corresponding average motor step lengths, which demonstrates a good linearity across the total operation range.


Fig. 4: Dependence of the motor step length on the length of individual moves from limit switch to limit switch in both directions.

The overall averaged motor step length is $14.982 \pm 0.002 \mu \mathrm{~m}$, and the corresponding number of motor steps it takes to move from limit switch to limit switch averages to $7325.4 \pm 0.8$ steps. The positional uncertainty of the drives is therefore within the length of one motor step. These tests included the variation of the switching point positions of the limit switches, which confirmed their stability.

## Examination of the speed of positional changes

The voltage readings of the potentiometers as input signal to a cathode ray oscilloscope served to observe the path-time profiles of the drives. The controller program of the stepping motors permits the base speed, the acceleration and deceleration time and the maximum speed to be set with a trapezoidal velocitytime profile. The base speed is set to $10 \mathrm{~mm} / \mathrm{s}$. In the case of a typical treatment energy variation, corresponding to a short step length of $\sim 1.2 \mathrm{~mm}$, the acceleration and deceleration time determines the total response time. In such cases, deceleration starts before the maximum speed is reached.


Fig. 5: The figure depicts a measured path-time profile with a step length of 2 mm , with the acceleration, deceleration time set to 25 ms , and the maximum speed set to $95 \mathrm{~mm} / \mathrm{s}$. The steepest slope of the path-time profile corresponds to a maximal speed of $\sim 60 \mathrm{~mm} / \mathrm{s}$. It takes 46 ms to complete a step of 2 mm , which is approximately the sum of the acceleration and deceleration times.

With the acceleration, deceleration time set to 20 ms , the maximum speeds of 50,60 and $70 \mathrm{~mm} / \mathrm{s}$ result in total response times of $\sim 44, \sim 40$ and $\sim 37 \mathrm{~ms}$, respectively for a step of 1.2 mm , corresponding to an energy change equivalent to 4.5 mm water.
Short response times require high accelerations. This increases the risk of losing steps and conflicts with the required reliability and accuracy of positional changes. As a compromise, the acceleration, deceleration time has been set to 20 ms and the maximum speed to $50 \mathrm{~mm} / \mathrm{s}$, respectively. If necessary, the maximum speed can easily be increased later.

## Operation temperature of the graphite absorbers

The electron beam-welding machine at PSI provided an adjustable electron beam that was well suited to examine the water cooling of the multi-wedge absorbers and to measure the temperature rise up to the maximum temperature, with and without water cooling. Numerically controlled by computer, the electron beam passes around a loop on the base of the wedges. This is connected to the flange of the drive assembly, which is water cooled.

Thermocouples record the temperature at six positions: At the upper and lower surface of the graphite absorber, in the middle and at the outer edges and at the flanging tube of the drive. In addition, the temperature of the cooling water at the inlet and outlet pipes was recorded. The test was carried out with the drive flanged to the vacuum chamber of the electron beam-welding machine.

The power of the electron beam was set to 90 W . This corresponds to the maximum beam load in the graphite absorber, which occurs at an extracted beam current of 500 nA and energy degradation from 250 to 70 MeV .


Fig. 6: Temperature rise of the graphite absorber as measured on the base of the multi-wedge by thermocouples, as recorded on a pen plotter.

The energy and the power of the electron beam amounted to 60 keV and 90 W , respectively, and the cooling water flow was set to $1.6 \mathrm{l} / \mathrm{min}$. The uppermost course of the temperature rise in Fig. 6 belongs to the temperature measured at the side edge, and the trace following slightly beneath it belongs to that measured in the middle of the upper surface. The third characteristic trace of the temperature was measured in the middle of the lower surface at the multi-wedge base. 70 to 80 minutes after starting, the temperature reaches an equilibrium temperature of $\sim 135^{\circ} \mathrm{C}$. The cooling water temperatures measured at inlet and outlet amount to $\sim 10$ and $\sim 20^{\circ} \mathrm{C}$, respectively. Without water cooling, an equilibrium temperature of $-220{ }^{\circ} \mathrm{C}$ was reached after about 30 minutes. The graphite absorber can easily withstand such temperatures for short periods.

## Examination of the desorption rate

Graphite absorbs large amounts of different gases, including atmospheric gases, water vapour and hydrogen, which extend the pumping time required to reach the operational pressure of $\leq 5 \times 10^{-5} \mathrm{mbar}$. The total surface area of all graphite components adds up to $\sim 0.5 \mathrm{~m}^{2}$. Even short exposures to air elongate the pumping time considerably. Various coating techniques have been investigated. They are summarised in the legend of Fig. 7 and Table 3.

| Power | Time | maxTemp. | Cooling |
| :--- | :---: | :--- | :--- |
| 90 W | 30 min | $-220^{\circ} \mathrm{C}$ | without |
| 90 W | 62 min | $-198^{\circ} \mathrm{C}$ | Air in water pipe |
| 90 W | 75 min | $-136^{\circ} \mathrm{C}$ | $1.6 \mathrm{I} / \mathrm{min}$ water |
| 90 W | 75 min | $-148^{\circ} \mathrm{C}$ | $0.63 \mathrm{I} / \mathrm{min}$ water |

Table 2: The highest equilibrium temperatures arose at the upper surface of the graphite absorber, in the middle of the multi-wedge base.


Fig. 7: The desorption rates of test pieces, each with a surface area of $300 \mathrm{~cm}^{2}$, measured at a pumping rate of $200 \mathrm{l} / \mathrm{s}$.

The $\mathrm{Al}_{2} \mathrm{O}_{3}$ plasma-coated test piece has a desorption rate similar to that of the pre-treated test piece (outgassed in vacuum for 24 hours at $500^{\circ} \mathrm{C}$ ), and also to that of the pumping unit, even after an exposure to air for $\sim 150$ hours. Besides the short pumping time, the $\mathrm{Al}_{2} \mathrm{O}_{3}$ plasma-coating of the surfaces of the graphite components also protects the surface against graphite rub-off, contamination and inhibits the release of tritium.

| Coating and pre-treatment | Time |
| :--- | :--- |
| electrochem. Cu-plated (neutral bath) | $>370 \mathrm{~h}$ |
| electrochem. Ag-plated | $>300 \mathrm{~h}$ |
| electrochem. Cu-plated (acid bath) | $>300 \mathrm{~h}$ |
| uncoated, 50 h air exposed | $\sim 13.2 \mathrm{~h}$ |
| uncoated, for $24 \mathrm{~h} 500^{\circ} \mathrm{C}$, in vacuum | $\sim 1.25 \mathrm{~h}$ |
| $\mathrm{Al}_{2} \mathrm{O}_{3}$-plated, exposed to air for 150 h | $\sim 1.25 \mathrm{~h}$ |

Table 3: Pumping time required to reach a pressure of $5 \times 10^{-5} \mathrm{mbar}$, at a pumping rate of $10 \mathrm{l} / \mathrm{s}$, estimated using the measured desorption rates.

The performance tests demonstrated fulfilment of the specifications, for all aspects of the operation and service. The pump-down time could be dramatically reduced by the introduction of $\mathrm{Al}_{2} \mathrm{O}_{3}$ plasma-coating of the graphite surfaces.

