MEASURED AND CALCULATED DOSE RATES IN AN ENTRANCE MAZE AT THE NEW PSI PROTON THERAPY FACILITY

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A new, superconducting cyclotron for medical applications is in operation since 2005 at the Paul Scherrer Institut. It delivers 250-MeV protons with a maximal beam intensity of 500 nA. Using a degrading system, the beam energy can be varied down to 70 MeV. During the commissioning phase, a test area was installed where the proton beam could be stopped in a Faraday cup. An entrance maze provided access to this area. To validate the calculational method used for the design of mazes, measurements of neutron and photon dose rates at four locations along the maze were performed. For these measurements, a 2-nA proton beam with energies of 250 MeV and 70 MeV was stopped inside the test area. The measurements are compared to calculational results using the Monte Carlo transport code MCNPX and the analytical code for the design of ducts and labyrinths, DUCT-III.

I. INTRODUCTION

The Paul Scherrer Institut (PSI) has been involved in the field of proton therapy since 1984: first, with the treatment of eye tumors (OPTIS) and, starting in 1996, with the treatment of deep-seated tumors using a scanning proton beam and a gantry. The very successful operation of these facilities and the international interest in the techniques developed there has prompted PSI to launch the project "PROSCAN" with the aim to further develop proton therapy at this institute. A new, superconducting 250-MeV cyclotron manufactured by ACCEL Instruments ("COMET") has been installed in 2004 and is dedicated to medical applications.[1] Commissioning tests started in 2005 and since February 2007 patients are being treated. Three new irradiation rooms will be put into service within a year. The nominal maximal beam intensity to be extracted from COMET is 500 nA. The beam energy can be varied from 250 MeV down to 70 MeV using a degrading system.

During the commissioning phase, a test area was installed where the proton beam could be stopped in a Faraday cup made of aluminium (see Fig. 1). To validate the calculational method used for the design of mazes, measurements of neutron and photon dose rates at four locations along the maze were performed. They are compared to results using the Monte Carlo transport code MCNPX (Ref. 2) and the analytical code for the design of ducts and labyrinths, DUCT-III (Ref. 3).

II. MEASUREMENTS

The layout of the test area with entrance maze and the four detector positions is shown in Fig. 1. About 2 nA of 250-MeV and of 70-MeV protons were stopped in the aluminium Faraday cup; the setup is shown in Fig. 2. The Faraday cup was 20 cm long in the beam direction and had a cross section of 5x5 cm^2. All walls are made of normal concrete with a density of 2.4 g/cm^3.

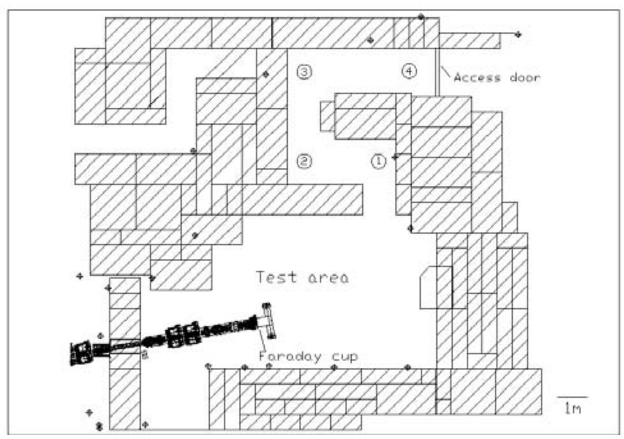

Fig. 1: Layout of the test area with detector positions 1-4. The beam enters from the left and is stopped in the aluminium Faraday cup. The room height within the test area is 2.5 m, within the maze 2.0 m.

Neutron dose rates were measured with Berthold LB 6411 proportional counters, gamma dose rates with Berthold LB 6500-4 stationary systems using the LB 111 analyzing electronics. Both detector systems have a lower detection limit of 0.1 μSv/h. The sensitivity range of the LB 6411 neutron detector lies between 10 meV and 20 MeV, of the gamma detector between 55 keV and 2 MeV. Fig. 3 shows the detector setup at position 3.

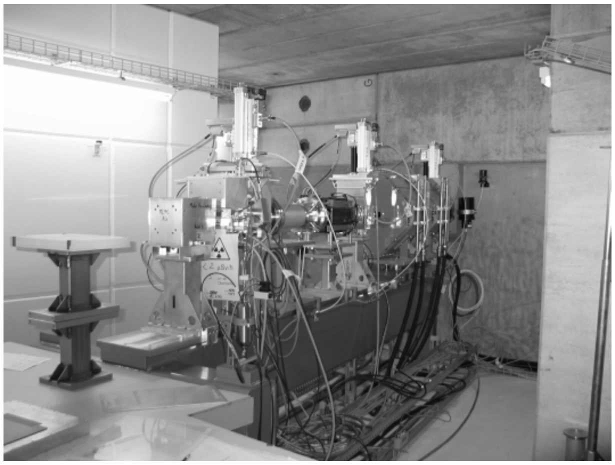

Fig. 2: Beam line with Faraday cup in the test area.

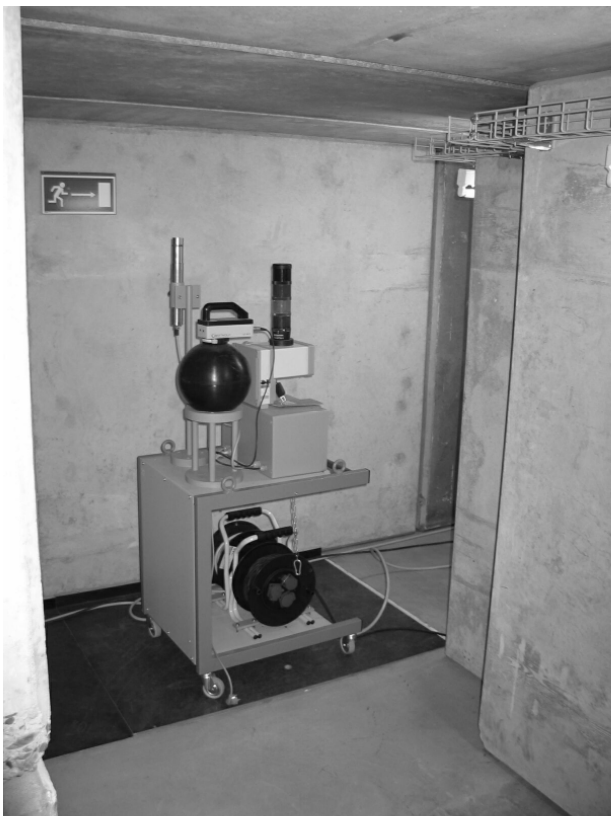

Fig. 3: Neutron and gamma detectors at position 3.

The dose rates were recorded every minute over a period of about 20 minutes. The precise beam current during this period was also recorded every 1-5 seconds. Both dose rates and beam current were averaged over the whole measurement period, and those average dose rates were then scaled to a beam current of 2 nA. The results are given in chapter V.

III. CALCULATIONS WITH MCNPX

The Monte Carlo particle transport code MCNPX version 2.6.B (Ref. 4) was used to calculate neutron and gamma dose rates at the detector positions in the entrance maze of the test area. Except for the Faraday cup, the beam line was not modelled. Cross sections for the materials were taken from the LA150 libraries using the following composition, in atomic fractions, for concrete: H 0.1064, C 0.2530, O 0.4446, Mg 0.0233, Al 0.0075, Si 0.0213, Ca 0.1415, Fe 0.0024.

The detectors were represented by void spherical cells with radius 15 cm. Track length estimates of particle cell flux (F4 tally) were folded with dose conversion factors and normalized to a proton beam intensity of 2 nA to obtain dose rate results to be compared to the measurements. Dose conversion factors for neutrons up to 100 MeV were taken from Ref. 5, above that from Ref. 6. Photon conversion factors were taken from Ref. 7.

A fine mesh with (20 cm)^3-cells was superimposed on the geometry and used to iteratively generate mesh-based energy-dependent weight windows with the bin structure (0.01, 0.1, 1, 19, 100, 250) MeV for variance reduction. In addition, point detectors were placed at the detector positions which yielded neutron dose rates with good statistics within a reasonable time frame. The point detector results agreed with the F4-tally calculations within the statistical uncertainty.

Fig. 4 shows the results of a neutron dose rate mesh tally with superimposed MCNPX geometry for the case of 250-MeV protons. The calculated dose rates at the detector positions are shown in chapter V.

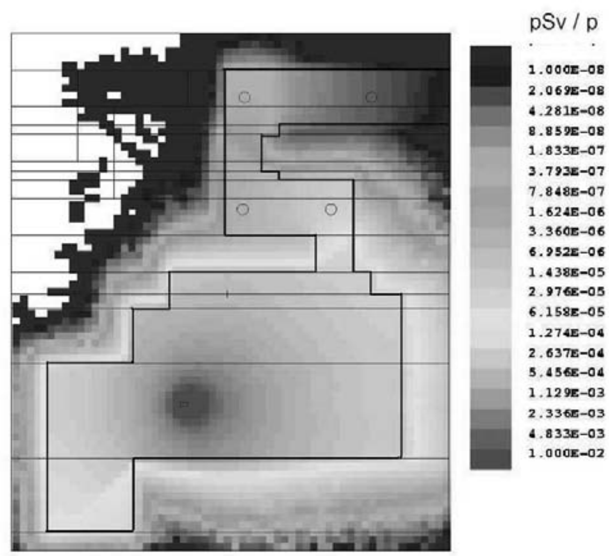

Fig. 4: Results of a neutron dose rate mesh tally calculated with MCNPX for the case of 250-MeV protons.

IV. CALCULATIONS WITH THE DUCT CODE

For comparison, the neutron dose rates at the detector positions were also calculated with the analytical code DUCT-III (Ref. 3). The input to DUCT includes the following parameters:

- material of the walls,
- geometry of the maze (only uniform leg lengths and height are possible),
- position of the neutron source relative to the maze entrance,
- energy-dependent neutron source in units of n/s using 12 energy groups up to 3 GeV,
- energy-dependent dose conversion coefficients.

The code assumes an isotropic source. Scattering contributions from the surrounding walls of the room are taken into account under the assumption that the source is located in a sphere with a radius corresponding to the distance from the source to the maze entrance. Dose rates are calculated in 41 equidistant steps along the length of each maze leg.

The lengths of the four maze legs are measured between center points: leg 1 is 1.75 m long, leg 2 2.50 m, leg 3 3.00 m and leg 4 4.00 m. Since the leg widths are not uniform, varying between 1 m and 1.5 m, the average leg width of 1.38 m was used. The height of the maze is 2.00 m.

MCNPX was applied to calculate the neutron source strength and spectrum at an angle of 35°, the angle between beam direction and maze entrance, for 70- and 250-MeV protons incident on the Faraday cup. The calculated values for the energy-dependent neutron emission per steradian and incident proton were normalized to a proton beam of 2 nA and to an isotropic source (i.e., multiplied with 4π). TABLE I lists the resulting neutron sources used as input to DUCT. It also includes the applied neutron dose conversion factors, which are based on Refs. 5 and 6.

TABLE I: Energy bins in DUCT (upper energies) with corresponding neutron dose conversion factors and neutron sources, for 250- and 70-MeV incident protons, used as input.

E-bins [MeV]	conv. factor [pSv cm^2]	source 250 MeV [n/s]	source 70 MeV [n/s]
0.0865	100	$1.55\ 10^8$	$5.43\ 10^6$
1.35	300	$1.45\ 10^9$	$6.26\ 10^7$
20	430	$2.46\ 10^9$	$1.83\ 10^8$
100	500	$3.07\ 10^9$	$9.02\ 10^7$
400	300	$2.15\ 10^9$	-

The calculated neutron dose rates at the detector positions are given in chapter V.

Since the photon dose rate at the maze exit is dominated by photons produced by neutron reactions in the maze walls, DUCT cannot be applied to calculate this value.

V. RESULTS AND DISCUSSION

All measurement and calculation results for the case of 250-MeV incident protons are summarized in TABLE II, those for 70-MeV incident protons in TABLE III. The uncertainties of the measurement results are about 30% for the neutron dose rate and about 15% for the gamma dose rate. The statistical uncertainty for the MCNPX results is of the order of 2%.

TABLE II: Results of measurements and calculations at the four detector positions for 250-MeV incident protons.

	Det. 1	Det. 2	Det. 3	Det. 4
n-dose [µSv/h]				
measured	1166	196	21	0.4
MCNPX	1317	213	22	1.9
DUCT	2470	325	27	1.8
γ-dose [µSv/h]				
measured	58	16	2.5	0.15
MCNPX	33.0	8.4	1.2	0.15
total dose [µSv/h]				
measured	1224	212	23	0.5
MCNPX	1350	221	23	2.0

TABLE III: Results of measurements and calculations at the four detector positions for 70-MeV incident protons.

	Det. 1	Det. 2	Det. 3	Det. 4
n-dose [µSv/h]				
measured	91	13	1.1	0.03
MCNPX	70	9.2	0.8	0.1
DUCT	78	10.2	0.8	0.06
γ-dose [µSv/h]				
measured	5.1	1.4	0.2	0.03
MCNPX	1.9	0.5	0.1	0.01
total dose [µSv/h]				
measured	96	14	1.3	0.06
MCNPX	72	9.7	0.9	0.1

According to the MCNPX calculations, neutrons above 10 MeV contribute only about 2% or less to the total neutron flux at the detector positions. Thus, the error due to their missing contribution in the measurement (because the neutron detector sensitivity only goes up to 20 MeV) should be small.

The total dose rate is dominated by neutrons, which contribute about 90% and more. Figures 5 and 6 show a comparison of the measured neutron dose rates with those calculated by the two different calculational methods.

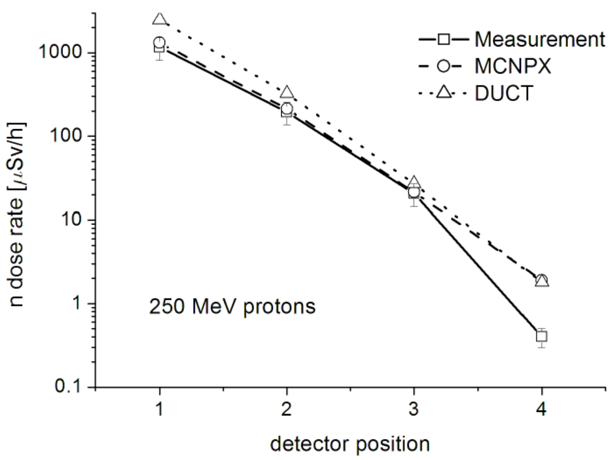

Fig. 5: Comparison of measured and calculated neutron dose rates at the detector positions for the case of 250-MeV incident protons.

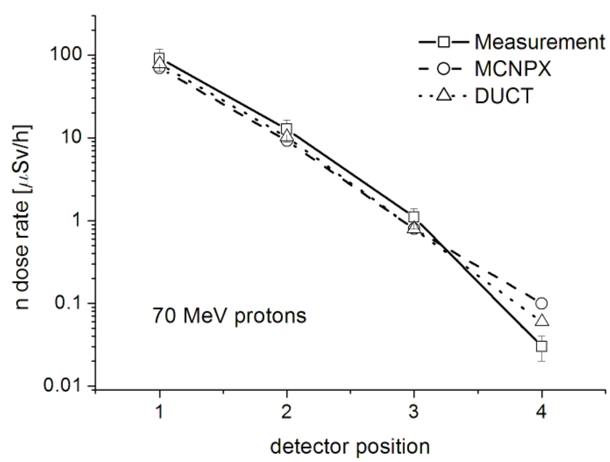

Fig. 6: Comparison of measured and calculated neutron dose rates at the detector positions for the case of 70-MeV incident protons.

The rather steep decline of the measured neutron dose rate between the third and fourth detector positions, as compared to the behaviour up to the third detector, seems to indicate that most probably there was a problem with the measurement at position 4. In part, this could be due to the low dose rates at this position. At least for the 70-MeV case also the calculated neutron dose rates are at or below the detection limit.

Except for the fourth detector position, the agreement between measured and calculated neutron dose rates is very good and in general within the error bars of the measurement. For the 250-MeV case, the DUCT results for the first two detectors are higher by a factor of about two. For the 70-MeV case, the calculated dose rates are consistently lower than the measurement (except for detector 4), but still within the measurement uncertainty.

The measured gamma dose rates are a factor of 2-3 higher than calculated with MCNPX.

VI. CONCLUSIONS

This comparison demonstrates that the analytical code DUCT-III can be reliably applied to the design of ducts and labyrinths within the investigated energy range, using neutron source data calculated with MCNPX. It is a very fast method compared to a calculation of the whole problem with MCNPX, where the optimization of the necessary variance reduction methods is a rather time-consuming process.

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