NEUTRON DOSES DUE TO BEAM LOSSES IN A NOVEL CONCEPT OF A PROTON THERAPY GANTRY

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Abstract

A novel design of a gantry for proton therapy is investigated in which a degrader and emittance limiting collimators are mounted on the gantry. Due to the interactions of protons in these components there will be an additional neutron dose at the location where a patient is positioned during a proton therapy. The results of numerical study of this additional dose are presented. Neutron prompt dose at the patient position is estimated through the Monte Carlo simulation using the MCNPX 2.7.0 particle transport code. Secondary neutron and photon fluxes from the distinct beam loss points are taken into consideration and the resulting dose is calculated using realistic estimates of beam losses. The dependence of the dose on the beam energy and individual impacts of each loss point on the total dose at the patient position as well as on critical beam line components are estimated and potential design constraints are discussed. It has been found that compared with a conventional gantry the expected additional dose is higher but the optimization of the beam line configuration and additional shielding shall help to reduce the dose to an acceptable value.

NOVEL GANTRY CONCEPT

A recently presented novel concept of a gantry [1] is aimed at the single room solution for the radiation therapy with protons through locating the energy degrader system (EDS) directly on the gantry itself. The existing EDS followed by an energy selection system (ESS), for example the one used at the Center for Proton Therapy at PSI [2] at the COMET cyclotron [3], typically require a space in the facility of about 10 m in length. With the proposed novel gantry concept it is foreseen that the elimination of the ESS and the shift of the EDS shall allow for simplifying and shortening the beam delivery line.

A sketch of the schematic layout for the considered beamline is shown in Fig. 1. The proton beam of fixed energy delivered by the accelerator is first deflected by 45° by a normal conducting (NC) dipole and then is directed towards the patient position by a compact superconducting (SC) magnet that provides the final 135° bend. The energy degrader is located on the gantry, right downstream from the NC dipole, to minimize the impact of protons scattered on the degrader on the beam transport. Two additional collimators downstream of the energy degrader shall allow for shaping the beam to match the acceptance of the SC magnet. The primary collimator shall define the beam size and the secondary collimator shall define the beam divergence.

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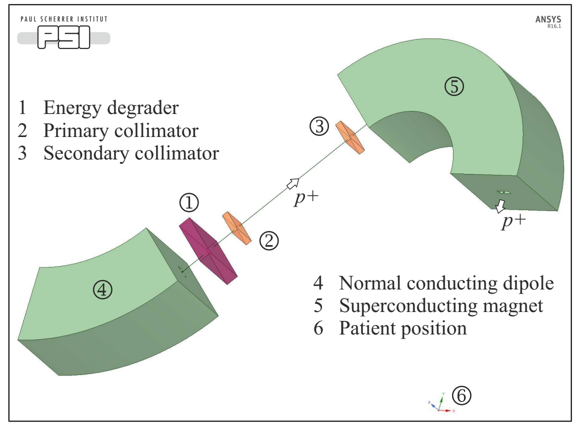

Figure 1: Beamline layout of "degrader on gantry" concept.

In the proposed solution three major points of beam losses — energy degrader and two collimators — are combined into a single drift space located in the beam waist allowing for compacting the EDS at the ~ 2 m length. However in such design the EDS is shifted closer to the patient position and so relative and absolute prompt neutron dose at the patient position arising from the losses at the beam transport through the EDS shall be estimated.

ESTIMATED BEAM LOSSES

The losses at the beam transport were calculated in the geometry model of the existing EDS of the COMET cyclotron.

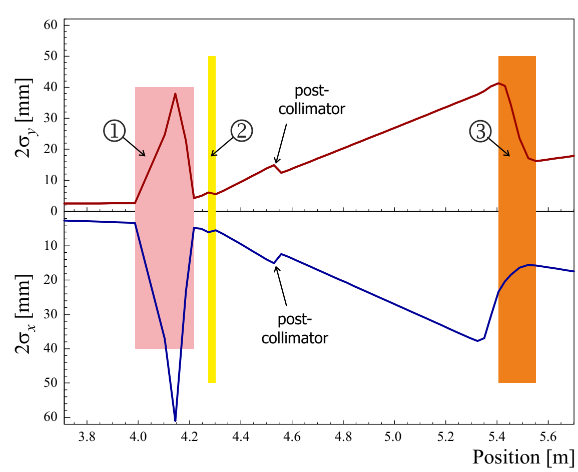

Figure 2: The beam envelope of $2\sigma_{x,y}$ simulated for the energy setting of 70 MeV for the EDS layout of the COMET cyclotron. Same labels as in Fig. 1. The losses at the post-collimator, downstream from the primary collimator, were included into the losses at the primary collimator.

Table 1: Estimated factors of beam intensity reduction and absolute beam losses for three considered loss points, and calculated factor of transmission and number of protons onto the degrader for a given transmission and a typical field dose, for the energy setting of the degrader of 70 MeV and 230 MeV. Same notation as in Fig. 1.

Energy setting		**70 MeV**	**230 MeV**
Beam intensity reduction factor			
1	Energy degrader	0.642	0.939
2	Primary collimator	0.242	0.829
3	Secondary collimator	0.121	0.494
Absolute losses			
1	Energy degrader	35.80 %	6.10 %
2	Primary collimator	48.66 %	16.06 %
3	Secondary collimator	13.66 %	39.39 %
Factor of transmission		1.88 %	38.45 %
Protons onto degrader		5.32×10^{12}	2.6×10^{11}

The beam envelope of $2\sigma_{x,y}$ was simulated with the OPAL charged particle tracking tool [4] as shown in Fig. 2 and the reduction of the beam intensity at each EDS component was estimated. For two energy settings of the degrader estimated beam intensity reduction factors and calculated from them absolute beam losses are given in Table 1. To deliver a typical field dose of 1 Gy over a volume of one liter, approximately 10^{11} protons are needed at the patient. Using this number as an initial normalization and the factor of transmission as calculated from the values for the absolute losses, Table 1 gives for each energy setting the estimated number of protons that shall be delivered onto the degrader.

NEUTRON DOSE SIMULATION

The distribution of secondary neutrons in the proposed beamline layout and resulting prompt neutron dose at the patient position were simulated using the MCNPX 2.7.0 Monte Carlo particle transport code [5]. Geometry models of simulations were designed in SpaceClaim Direct Modeller from the ANSYS Workbench 16.1 [6] as depicted in Fig. 3 and then automatically converted to the MCNPX geometry description using the SuperMC simulation software system which is developed by INEST-FDS Team [7, 8].

The primary proton beam energy was set to 250 MeV. Two cases of the energy setting of the degrader of 70 MeV and 230 MeV were simulated. The dimensions of the degrader were taken according to the given energy setting using the stopping-power and range data for protons from the PSTAR database [9]. As at the time the simulations have been performed the technical design of the collimators was not yet fixed, the thickness of primary and secondary collimators in the beam direction corresponded to 110 % of the range of 70 MeV and 230 MeV protons respectively, as shown in Fig. 3, so that all protons will be stopped within the collimator material. The energy degrader was simulated as a solid graphite block. The same block geometry using copper as a material was assumed for both collimators. The geometry of both NC dipole and the SC magnet was approximated by a solid curved parallelepiped made out of steel with a rectangular magnet aperture.

Table 2: Neutron dose [μSv] at the patient position for a typical field dose and its relative fraction for beam losses at three considered loss points and the energy setting of the degrader of 70 MeV and 230 MeV. Same notation as in Fig. 1.

Energy setting		**70 MeV**		**230 MeV**	
1	Energy degrader	764	85 %	9	15 %
2	Primary collimator	100	11 %	12	20 %
3	Secondary collimator	33	4 %	39	65 %
Total dose		897 μSv		60 μSv	

RESULTS AND OUTLOOK

The simulated 2D distributions of the neutron dose per primary proton are shown for each individual beam loss point in Fig. 4. The neutron dose at the patient position was obtained by normalizing these neutron dose maps by the absolute number of incoming beam particles as calculated from the values of absolute losses from Table 1. The resulting partial and total neutron dose for two simulated cases of the energy setting of the degrader is given in Table 2.

The simulations showed a non-negligible additional dose from neutrons at the patient position of an order of 1 mSv for a typical field dose, at the energy setting of 70 MeV. The neutron dose at 230 MeV was found factor 15 lower which is almost proportional to the difference in the primary beam intensity as seen from Table 1. The main contribution to the total neutron dose was found from the “thick” insertions in the beamline in combination with a relatively high energy of the incoming beam. These “thick” insertions are the energy degrader in the case of 70 MeV and primary and secondary collimators in the case of 230 MeV, as seen also from the neutron dose maps in Fig. 4.

In the final gantry design the thickness of the collimators will be chosen to be fixed according to the highest energy setting of the degrader. At lower energy settings this shall result in additional interactions of secondary particles in the collimators. Supplemental simulations show that the subsequent change of the neutron dose at the patient position will be in the order of only several percents relative to the total dose as listed in Table 2. Also in the present geometry model of simulations only a bare beamline has been introduced which definitely corresponds to an extreme maximal magnitude of the secondary neutron flux at the patient position, produced by the lost protons. One can assume that the appropriate radiation shielding together with further optimization of the beamline layout will certainly allow for reducing the estimated neutron prompt dose.

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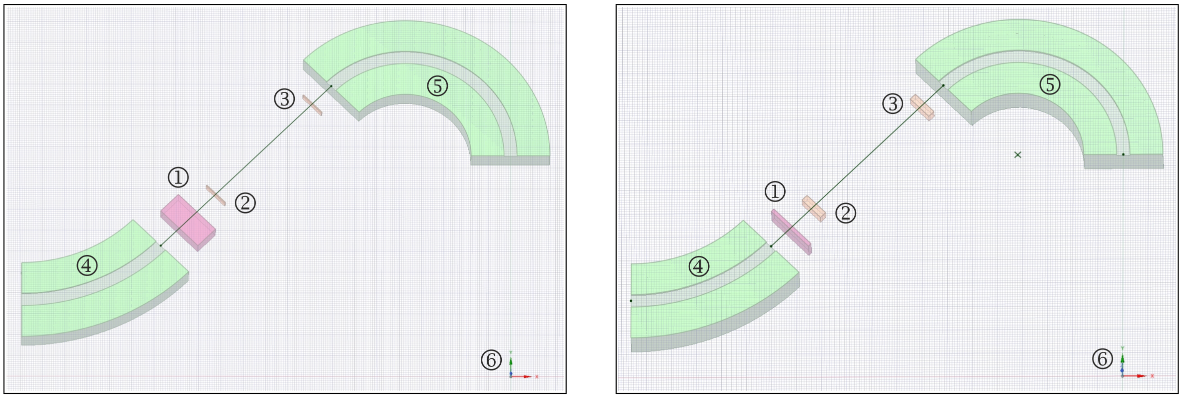

Figure 3: Simulation models for the energy setting of 70 MeV (left) and 230 MeV (right). Same labels as in Fig. 1.

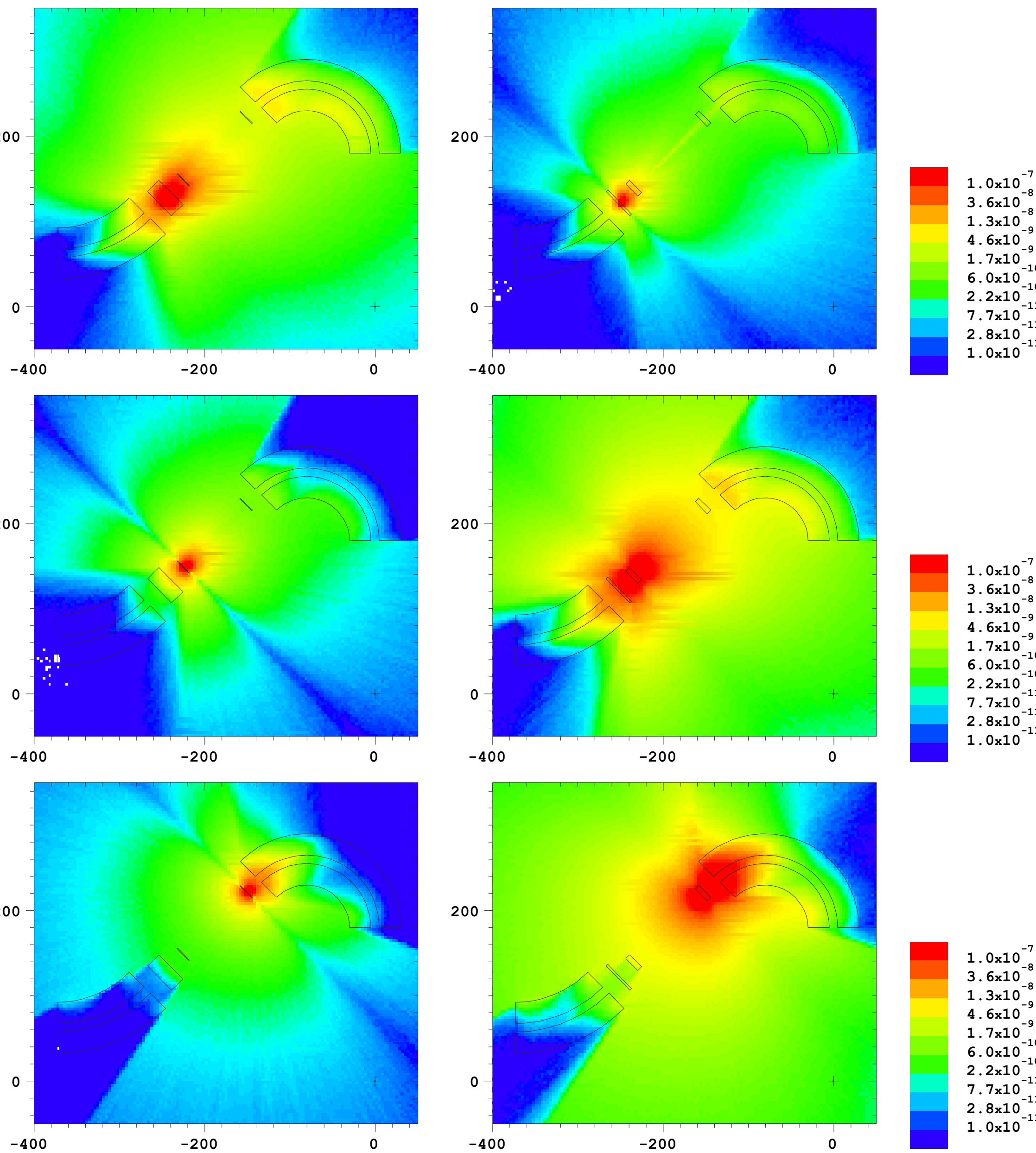

Figure 4: Neutron dose [μSv] per primary proton for the case of the beam impinging onto the degrader (1st row), primary (2nd row) and secondary collimator (3rd row) when degrading to 70 MeV (left column) and to 230 MeV (right column).

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