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THE MONTE CARLO SIMULATION FOR THE RADIATION PROTECTION IN A NOZZLE of HUST-PTF*

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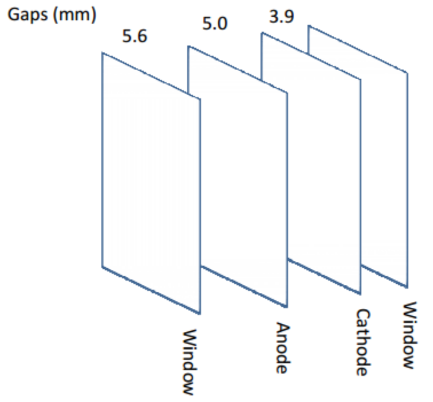
Abstract

Nozzle is the core component in proton therapy machine, which is closest to the patient and is necessary to consider the radiation impacts on patients and machine. The ionization chamber and the range shifter in active scanning nozzle are the main devices in the beam path that affect the proton beam and produce secondary particles during the collision, causing damage to the patients and machine. In this paper, the spatial distribution of energy deposited in all regions, the distribution of the secondary particles of 70-250MeV proton beam in the nozzle in Huazhong University of Science and Technology Proton Therapy Facility(HUST-PTF) are studied with Monte Carlo software FLUKA in order to provide reference for radiation shielding design. Six types of materials commonly used today as range shifters are analyzed in terms of the influence on radiation,so that the most suitable material will be selected.

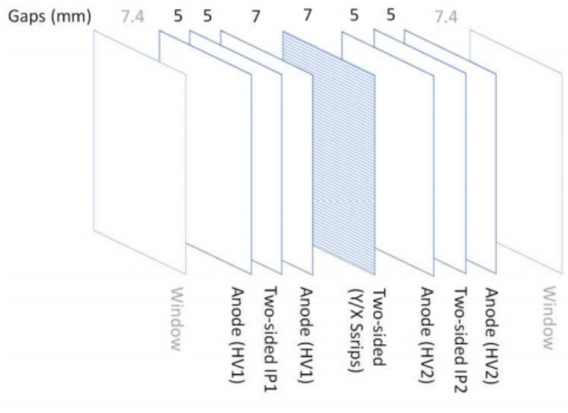
INTRODUCTION

In order to ensure the safety of the patients, as well as the machine, the effect of radiation should be considered when designing the nozzle. Due to the application of the active scanning nozzle in HUST-PTF, the collimator and scatter are not required on the beam path, so the scattering and secondary particle radiation will be significantly reduced[1].However, it is still necessary to analyze the radiation distribution in the nozzle and develop a corresponding radiation shielding scheme. At the end of nozzle, a range shifter is placed very close to the patient in order to decrease the proton beam energy so that the shallow tumors can be treated. Selecting a suitable material for the range shifter will significantly reduce its radiation impacts on patients.

The scanning nozzle is mainly composed of a vacuum window, a pixel ionization chamber, a helium pipe, an ion chamber, and a series of mechanical support structures in Huazhong University of Science and Technology Proton Therapy Facility(HUST-PTF). The vacuum window, made of 30μm kapton, is installed at the end of the beamline as a boundary between the beamline transmission system and the nozzle system. The pixel ionization chamber is used to monitor the initial beam states which is located 100mm away from the vacuum window. The helium pipe, passing through two scanning magnets, is placed behind the pixel ionization chamber to reduce energy loss and transverse scattering. The plate ion chamber is placed 800 mm from the isocenter plane and is used to monitor the position and the dose of the proton beam，so that the accuracy of the dose and position can be ensured. The structure of pixel ionization chamber and plate ion chamber in HUST-PTF is shown in Fig.1. In order to simulate the human body composition, a water phantom is placed after the isocenter plane. The structure of nozzle in HUST-PTF is shown in Fig. 2.



a. The structure of pixel ionization chamber



b. The structure of plate ion chamber

Figure 1: The structure of pixel ionization chamber and plate ion chamber.

In this paper, the model of the nozzle in HUST-PTF is constructed in three dimensions by using the Monte Carlo software FLUKA[2]. The energy loss when the proton beam passes through the nozzle，the secondary particle yield, the spatial distribution of neutrons and photons are calculated by using FLUKA. At the same time, the

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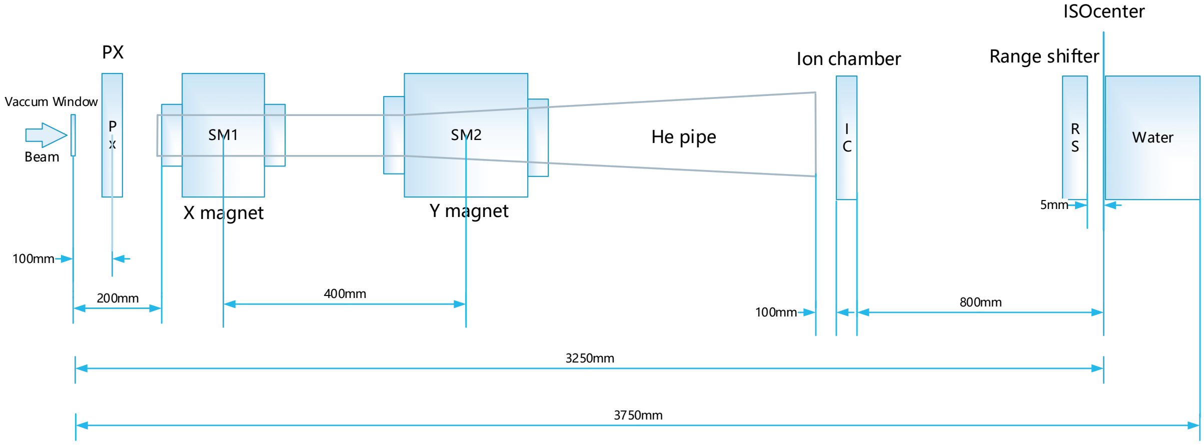


Figure 2: The structure of the nozzle in HUST-PTF.

influence of range shifters made of different materials are also calculated.

SPATIAL DISTRIBUTION OF ENERGY DEPOSITED IN NOZZLE

Due to the Coulomb's scattering in the air and the collision with the materials, the energy loss and transverse scattering of proton beam in the nozzle will be brought. The energy loss of proton beam will affect the beam quality and should be calculated in all regions. The three-dimensional structure of the nozzle in HUST-PTF is constructed in FLUKA (as shown in Figure 2), and the energy loss of the 70-250 MeV proton beam in the nozzle has been calculated.The number of protons is 5×10^6. The results are listed in Table 1.

Table 1: The Energy Loss of Beam in Each Region of the Nozzle

Region	Proton energy/MeV			
	70		250	
	Energy Loss /MeV	Percentage of Initial Energy (%)	Energy Loss /MeV	Percentag e of Initial Energy (%)
Pixel IC	0.021	0.03	0.002	0.0008
He Pipe	0.087	0.124	0.034	0.0136
Plate IC	0.074	0.106	0.008	0.0032
Air gap	1.098	1.569	0.476	0.1904
Total	1.28	1.829	0.52	0.208

The larger the proton beam energy is, the smaller the energy loss is brought throughout the nozzle. Also, the energy loss mainly emerges in the air gap, and the losses in the pixel ionization chamber, the helium pipe, and the ion chamber are small. Since the energy loss generated in each of the main components is small, the thermal effect is not significant and the treatment requirements can be meet. As is shown in Fig.3, the main energy losses are concentrated in the water phantom.

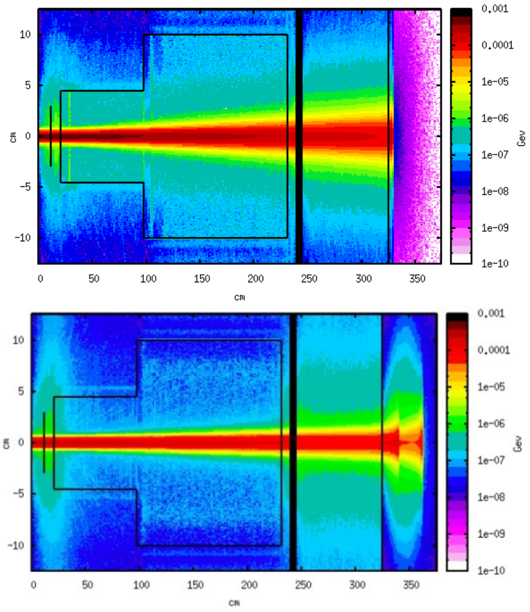


Figure 3：2D distribution of energy deposition of 70MeV（upper）/250MeV(lower) in the nozzle in HUST-PTF.

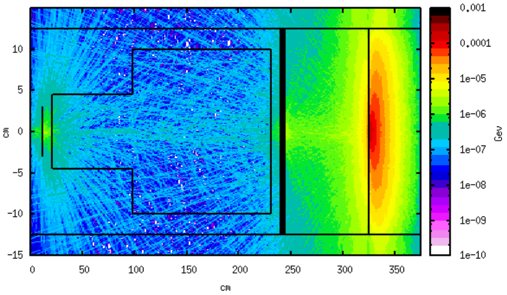
THE DISTRIBUTION OF THE SECONDARY PARTICLES OF 70-250MEV PROTON BEAM IN THE NOZZLE

During the transmission in the nozzle, elastic and non-elastic collision with the nuclei of different materials will happen, producing a large number of secondary particles that will adversely affect the patient and reduce the machine's expected service life. So it is necessary to calculate the distributions of secondary particles. Number of secondaries generated in inelastic interactions per beam particle when proton beam pass through the nozzle is shown in Table 2.

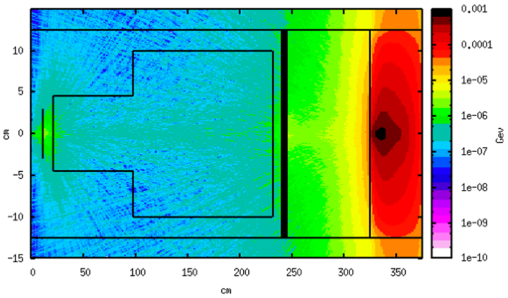
Table 2: Number of Secondaries Generated in Inelastic Interactions per Beam Particle

Particle category	Prompt radiation		
	70MeV	150MeV	250MeV
4-HELIUM	29.4%	23.4%	20.3%
3-HELIUM	0.7%	1.1%	1.2%
TRITON	0.3%	0.6%	0.7%
DEUTERON	1.6%	2.1%	2.3%
PROTON	42.9%	42.6%	43.3%
PHOTON	15.4%	12.1%	10.5%
NEUTRON	9.8%	18.0%	21.6%

It can be seen that the α particles, neutrons and photons are the main secondary particles generated in the collision during the beam transmission in the nozzle. As the proton beam energy increases, the number of neutrons produced will increase significantly and the number of photons will decrease. In the radiation shielding design, the main consideration is the shielding of the neutrons, so it is necessary to calculate the distribution as well as the fluence, so that a corresponding shielding scheme should be established. The two-dimensional distribution of neutrons and photons is shown in Fig.4 and Fig.5 :



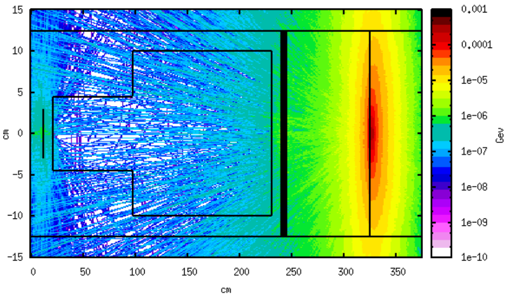
a.70MeV neutron two-dimensional distribution.



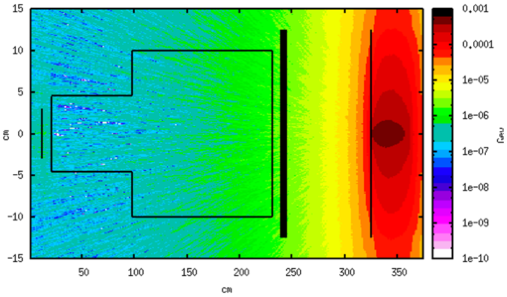
b.250MeV neutron two-dimensional distribution.

Figure 4:Neutron two-dimensional distribution.

From the diagram of the neutron two-dimensional distribution, it can be seen that during the transport of the proton beam in the nozzle, there will be neutrons gathered around the pixel ionization chamber, after the plate ionization chamber, and in front of the water phantom. Corresponding shielding devices should be placed in these areas and the electronic equipment should not be in the vicinity.



a.70MeV photon two-dimensional distribution.



b.250MeV photon two-dimensional distribution.

Figure 5: Photon two-dimensional distribution.

Currently used neutron shielding materials are concrete, aluminum, stainless steel and some new materials. One of the materials is made of boron carbide as a functional filler and epoxy resin as a matrix material. It has good neutron shielding properties and strong absorption, and is suitable as a material for local neutron shielding. Therefore, a suitable neutron shielding facility should be installed at the end of the ionization chamber, in front of the water phantom and around the pixel ionization chamber.Also,the placement of electronic equipments at these locations should be reduced, thereby reducing the impact of neutrons on patients and machines.

INFLUENCE OF RANGE SHIFTER ON RADIATION

The range shifter, one of the important components for the nozzle system,plays a role in decreasing the energy of the proton beam at the end of the nozzle. By properly selecting the range shifter material, it is possible to significantly control the transverse scattering and decrease the damage to healthy tissue, as well as the radiation impacts caused by neutrons.

In this paper, the Monte Carlo method is utilized for analysis. Similar to the selection of materials in the reference paper[3], six materials are selected for analysis,and water is included as a reference material. Each material has the same water equivalent thickness(WET).

By comparing the fluence of neutrons produced after the proton beam passed through the range shifters, the material with the minimum radiation effect can be selected.The following model is constructed: the human body is simulated in a water phantom with a length, width and height of 40 cm, and the range shifter is placed 50 cm from the entrance of the proton beam, which is a vacuum section. The model is shown in Fig.6.

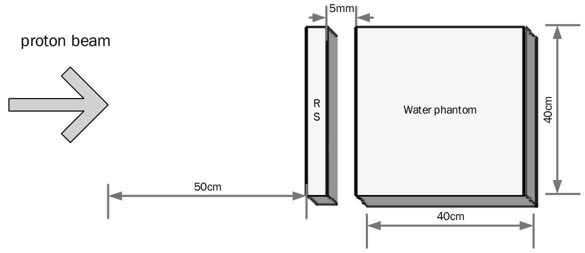


Figure 6: The model of the simulation for influence of range shifter on radiation.

In this simulation, the beam parameters before the range shifter is designed as the same,and the proton beam energy was set to 150 MeV.The neutron flux at the surface of the water phantom after the proton beam passed through a range shifter composed of different materials was calculated by using FLUKA. According to the proton energy, the neutron energy spectrum shown in Fig.7 is obtained.

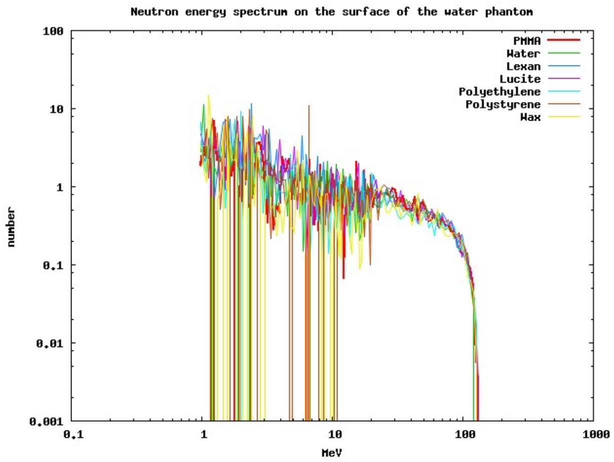


Figure 7: Neutron energy spectrum on the surface of the water phantom.

Neutrons can be divided into fast neutrons, medium energy neutrons, slow neutrons, and thermal neutrons according to the based on energy of the neutrons. The faster the neutron is, the harder it is to be absorbed. Since the position of the range shifter is already very close to the human body, no matter what kind of energy neutron, it will definitely enter the human body and be absorbed by the human body. Therefore, when considering the choice of range shifter materials, more attention should be paid to the comparison of the total flux of neutrons. Table 3 shows the comparision of the neutron fluence with different materials.

Table 3 Comparision of the Neutron Fluence

Material	Thickness (cm)	Neutron fluence		Total
		Neutron Energy/MeV		
		0~20	20~150	
Water	7	130.92	17.72	148.64
PMMA	5.44	144.30	13.34	157.64
Lexan	6.08	206.38	19.06	225.44
Lucite	5.99	179.92	17.72	197.64
Polyethylene	6.91	142.72	14.66	157.38
Polystyrene	6.64	184.45	17.97	202.42
Wax	7.00	120.21	16.14	136.35

It can be seen from the above analysis that when wax, PMMA and Polyethylene are used as the material of the range shifter, the number of neutrons generated is relatively small; while Lexan, Polystyrene will generate a large number of neutrons. From the perspective of the similarity with the characteristics of water, Wax, PMMA and Polyethylene will be better choices.

In practice, the selection of the material of range shifter should also consider the ability to decrease the transverse scattering、the processing costs as well as the strength and stability. From the perspective of radiation protection, Wax, PMMA and Polyethylene are more suitable as the range shifter materials.

CONCLUSION

During the transmission of the proton beam in the nozzle in HUST-PTF, the energy loss is mainly concentrated in the air gap, while the energy loss caused by the pixel ionization chamber, the helium pipe, and the plate ion chamber is small. Neutrons, photons, and α particles are the main secondary particles in the process. Among them, neutrons mainly appear around the pixel ionization chamber and water phantom. And as the energy increases, the neutron yield increases further. Photons also appear more in the air at the end of the nozzle. Neutron shielding facilities should be installed at the end of the ionization chamber, in front of the water phantom and around the pixel ionization chamber. Also, the placement of electronic equipment at these locations should be reduced. Wax, PMMA and Polyethylene are better choices as the range shifter materials when considering the radiation protection.

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