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RADIATION EFFECTS STUDY FOR BEAM LOSSES ON THE ELECTROSTATIC DEFLECTOR IN HUST SCC250

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Abstract

China has payed comprehensive attention to the study of proton therapy in recent years. Radiation effects induced by beam losses in compact, high energy superconducting cyclotrons are being taken into crucial considerations. The proton beam is extracted out of HUST SCC250 superconducting cyclotron by electrostatic deflectors. The fierce impinging between proton beam and the deflector septum is the main cause of beam losses, which will bring about radiation effects leading to activations in devices and coil quenching. This paper presents the simulation result of radiation effects between beam and septum by utilizing Geant4 code based on Monte Carlo method. The energy deposition of beam losses is figured. Meanwhile, the yields and energy distributions of secondary particles are investigated. The result focused on radiation effects will provide us with valuable implications for the design of this superconducting cyclotron.

INTRODUCTION

HUST SCC250, being developed for/at Huazhong University of Science and Technology, is a superconducting cyclotron applied for proton therapy. The extracted proton beam is expected to be 250MeV and the beam current is about 800nA. The electrostatic deflector in this cyclotron is the research subject of this paper, whose structure has been introduced in [1]. In real operation conditions, the deflector undergoes intense interactions with beam that will directly influence the beam quality and extraction efficiency. These interactions subsequently trigger severe cooling problem and radiation effects affecting the operating performance of the cyclotron. The cooling problem has been discussed in [1], then the radiation effects will be studied in this paper.

Radiation effects mainly exerts considerable influences on the operation of superconducting cyclotron from the following two aspects: the nuclear heating of the cryogenic magnet and radiation damage or activation of certain materials [2]. To gain a deeper insight into radiation effects, Geant4 toolkit has been used to simulate the radiation with the septum after impacted by proton beam. The energy deposition and secondary particles have been analysed which gives a reference to the future study and configuration of the cyclotron.

This paper is structured as follows: Section 2 introduces details on the simulation model and parameters employed in Geant4 toolkit, Section 3 presents results and discussion and then the conclusion is proposed in Section 4.

MATERIAL AND METHODS

Geant4 Toolkit

Geant4 is a software toolkit for the simulation of the passage of particles through matter [3]. It is applied in a variety of domains including high energy physics, space applications, medical physics and radiation shielding. Geant4 code, which is written in C++ programming language, earns much favour from a large number of researchers whereby its abundant particle data libraries and open-source capability. Since plenty of examples adapted to various occasions contains in Geant4 data package, the users can modify the example codes as they need to satisfy their applications. Moreover, self-defining simulation models and physics lists give users much more setting options.

It is noted that Geant4 10.1.2 edition is employed in this study and the application platform is Win10 x64 system.

Incident Beam Properties

As the proton beam is propagated down the +Z axis into the deflector, its transverse motion can be represented by two ellipses in the phase spaces [4] (X, X_P) and (Y, Y_P), where $X_P = P_x/P_z$, $Y_P = P_y/P_z$, represent respectively the beam angular divergences θ and φ, and P_x, P_y, P_z stand for the three components of the beam momentum. The phase ellipse is defined with Twiss parameters and beam emittance. The beam emittance is 1mm·mrad. Twiss parameters taken from beam dynamics calculation are tabulated in Table 1

Table 1: Margin Specifications

X planar	Y planar
$\alpha_x = -0.533862$	$\alpha_y = 0.219913$
$\beta_x = 1.303566$	$\beta_y = 0.668318$
$\gamma_x = 0.985764$	$\gamma_y = -1.568657$

Subsequently, the respective phase ellipse in X, Y directions and the beam profile in X-Y cross-section are plotted in Figure 1.

It is noteworthy to mention that Geant4 code package doesn't contain beam phase ellipse defining class so that users can only achieve this by employing mathematic manipulation. To define the phase space, the users should specify the four variables X, Y, X_P, Y_P into random Gaussian distribution respectively. Geant4 code provides the function--SetParticleMomentumDirection( ) for users to set the momentum direction of particles. The proton beam energy in our study is set to be monoenergetic 250 MeV.

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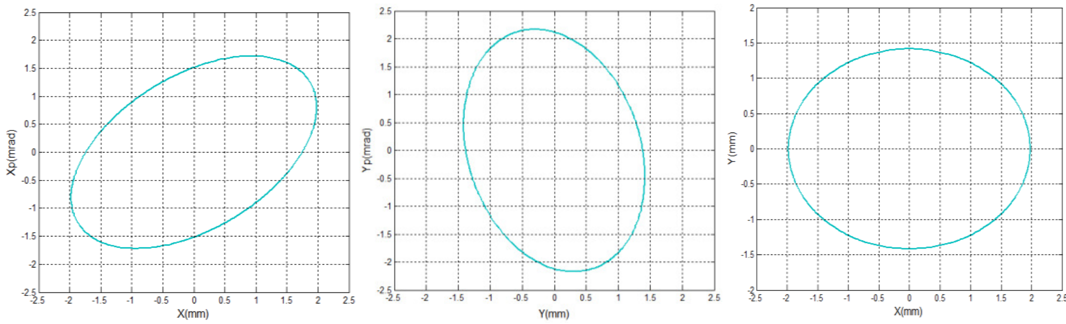

Figure 1: left: (X, X_P) phase ellipse; middle:(Y, Y_P) phase ellipse; right:(X, Y) beam profile.

Simulation Set-ups

To simplify the calculation, we establish 1/4 length of the overall deflector to be our simulation model whose 3D dimension is 50mm × 40mm × 120mm. The septum is made of Tungsten and only 0.3mm thick. While the liners and housing are copper styled. The model is placed in 2×10^{-5}Pa, 20℃ vacuum environment. Figure 2 displays the simulation model.

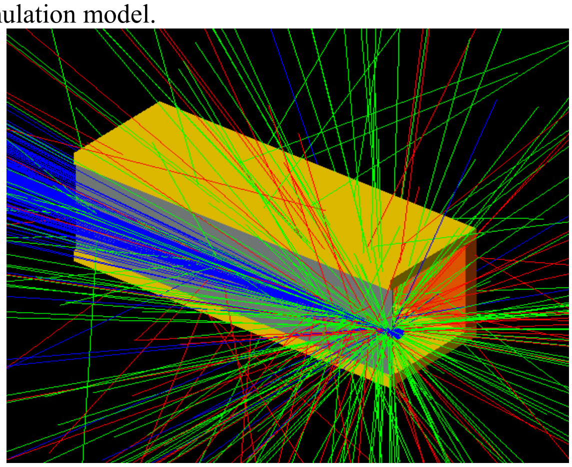

Figure 2: Simulation model in Geant4.

To make the best compromise between calculation accuracy and CPU time, we choose the FTRP_BERT from several physics lists [5]. The range cut is set to 0.1 µm, therefore the cutoff energy for transport is fixed to 0.01MeV. The monoenergetic 250MeV beam of 2×10^{6} protons irradiates the center of the septum lateral surface along +Z axis, inducing p-W nuclear interactions.

As shown in Figure 2, the incident proton beam (blue in the figure) impinges the septum producing numerous secondary particles, most of which are gammas (red in the figure) and neutrons (green in the figure). Gamma and neutron are also the types of secondary particles that contribute most to the radiation effects.

RESULTS AND DISCUSSION

Energy Deposition on the Septum

The energy deposition curve is plotted in Figure 3, when the 250MeV proton beam irradiates tungsten bulk and its energy is postulated to be completely deposited in the bulk. The maximum energy deposition locates in the depth of 37.7mm, which agrees well with the value calculated by SRIM software.

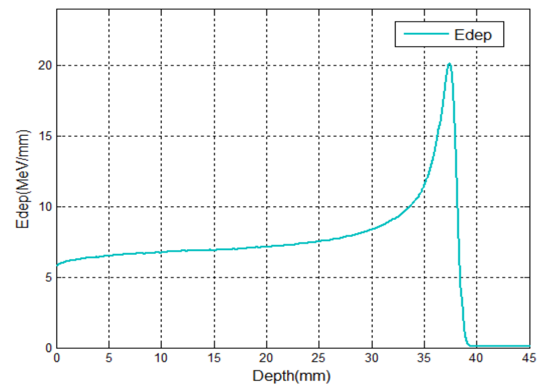

Figure 3: Energy deposition curve of 250MeV proton beam in tungsten.

Obviously the above curve cannot illustrate our simulation case, for the tungsten septum is so thin, only 0.3mm, that the energy of the proton beam won't be totally deposited in it. Figure 2 shows that thin septum splits the proton beam into diverse directions. Since the positon where the maximum energy deposition locates indicates the fiercest heating effect and nuclear interactions happening, it is essential to investigate the distribution of energy deposition on the septum shown in Figure 4.

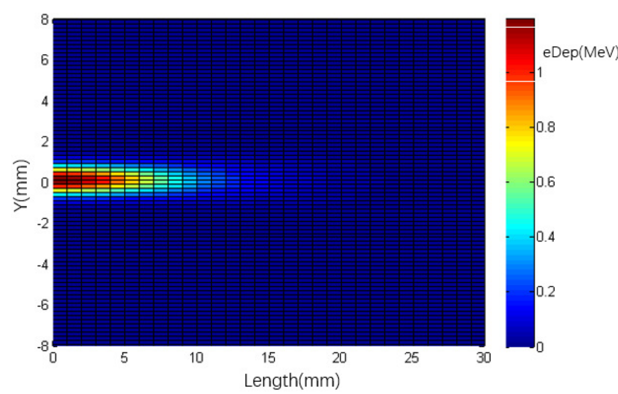

Figure 4: Distribution of energy deposition on the tungsten septum.

As displayed in Figure 4, the leading edge of the septum receives the maximum energy deposition. The dimension of the main energy deposition area reaches nearly

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20mm×3mm where the fiercest nuclear interactions happens. Maybe we can settle lower Z material in the front of the septum to weaken the nuclear interactions.

Energy Deposition of Secondary Particles on the Housing

Large amount of gammas and neutrons are generated due to the collision between proton beam and tungsten septum. Those secondary particles may penetrate the housing to hit on the superconducting coils possibly inducing quenching. Figure 5 presents the energy deposition of secondary particles on the housing.

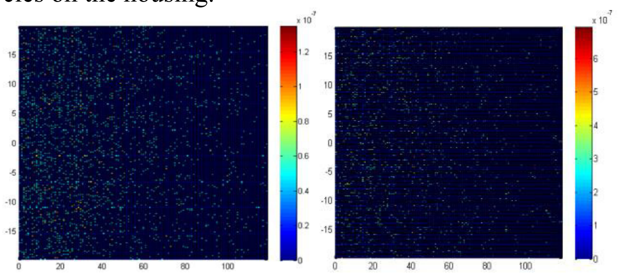

Figure 5: left: energy deposition of gamma; right: energy deposition of neutron.

We can see from Figure 5 that the energy depositions of gammas and neutrons on the housing are extremely tiny. The number of stopped secondary particles just accounts for less than 0.1% based on calculation which means that most of the secondary gammas and neutrons penetrate the housing and emanate to outer space. It is suggested that the material of housing should show an excellent performance to shield gammas and neutrons.

Yields and Energy Distributions of Secondary Particles

The ratio between secondary particles productions and beam source proton number present the yields of secondary particles existing from the target. The tabulated results of yields appear in Table 2.

Table 2: Yields of Gammas and Neutrons

Type	Yield
Gamma	0.11734
Neutron	0.26634

The energy distributions of outgoing gammas and neutrons are shown in Figure 6 and Figure 7. As shown in Figure 6, the energy of secondary gammas is relatively low mainly ranging from 0-8MeV and the number of 0-2MeV secondary gammas accounts for over half of the total. While the Figure 7 shows that the energy of secondary neutrons mostly settles in 0-50MeV and neutrons lower than 10MeV occupy nearly 90% of total. Those results may bring some implications for the radiation shielding designers.

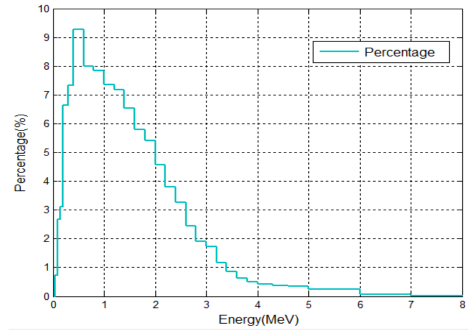

Figure 6: Energy distribution of secondary gammas.

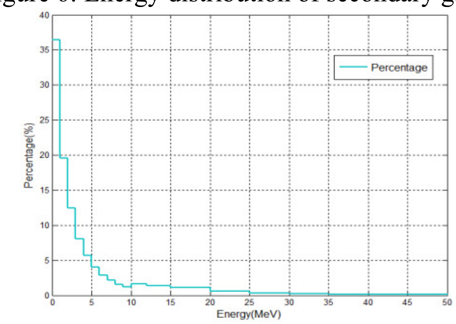

Figure 7: Energy distribution of secondary neutrons.

CONCLUSION

This paper exhibits a comparably detailed study into radiation effects caused by beam losses on the septum. The energy depositions on the septum and housing in the simulation demonstrate that radiation effects on the deflector deserves serious considerations. The yields and energy distributions of secondary particles provide useful implications for researchers when designing the radiation shielding structure. This study will be carried out more deeply in the near future.

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