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DESIGN OF A MULTI-LAYER FARADAY CUP FOR CARBON THERAPY BEAM MONITORING*

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Abstract

Because of determining the depth of Bragg Peak, range and energy of carbon beam are very important parameters in therapy. In order to measure those parameters rapidly, we design a multi-layer Faraday cup (MLFC). Simulation of proton beam and carbon beam are given in this paper. A prototype has 128 channels have been developed. Each consists of a 40 µm copper foil and 600 µm FR4 plate. A 128 channels electronics was used to measurement the deposited ions in each copper foil.

INTRODUCTION

China's first Heavy Ion Medical Machine (HIMM) developed by the Institute of Modern Physics (IMP) was approved to be registered at January 10, 2020. The main parameters at treatment place are listed in Table 1.

Table 1: Main Beam Parameters of HIMM

Parameters	Value
Ion	$^{12}C^{6+}$
Beam energy	80~430 MeV/u
Intensity at treatment room	(2 pA ~ 0.4 nA) 2e6 ~ 4e8 pps
Extraction time	2 s
Extraction cycle	8 s

It is very crucial that the difference between the radiation field achieved by patient and given by prescription is as small as possible. Two of most importance beam parameters which decide the radiation field are beam energy and beam energy distribution. Therefore, these parameters should be checked or calibrated before treating.

Overview of range verification of proton and light-ion beams have been given by W. T. Chu [1]. It involves ex vivo or off-line measurement method [2] and in vivo or online measurement method. MLFC (Multi Layer Faraday Cup) was proposed for testing Monte Carlo models [3]. And then it was first applied to verify proton range by Bernard Gottschalk at NPTC [4]. Now it has become a conventional tool and has been used in numerous proton therapy research center [5-13]. However, MLFC can only used for proton beam so far. Because, in proton therapy most of the primary particles will stop near Bragg Peak with no secondary fragments creation. But for carbon particles, there will be several charged secondary fragments such as H, He ,Li ,Be and B created. Those charged particles will be collected by charge meter as well as primary carbon particles.

After carefully analyzing the affection by secondary fragments and with Fluka simulation, the author find that the peak of beam charge collection curve was near Bragg Peak. So, we propose that use MLFC to measure carbon beam range and energy. In this paper, the measurement theory will be described firstly. And then, Fluka simulation result will be given. Finally, a prototype of MLFC are also given.

EXPERIMENT METHODS

Measurement Theory

The theory of MLFC is well-documented. A MLFC is a stack of metal collecting plates which separated from each other by thin insulating plates. MLFC is connected to a multi channel charge meter so that each active sheet of the MLFC is connected to one channel. Take proton beam for example, if a proton beam (for a therapy beam, beam energy are usually from 70 MeV to 250 MeV) inject into a MLFC, most proton particles will pass through several metal plates and insulating plate and stop near Bragg peak position in the last. When particles stop, each layer plate can collect the deposited charge. In other words, the MLFC can measure beam differential fluence as a function of depth [4].

As a result of statistical fluctuations, the effect of range straggling give a charge distribution. For a therapy proton beam, range straggling can be modelled by a Gaussian distribution [14-16]. Because proton is the lightest ion so no nuclear fragments created. Therefore, no extra charged particles or charged fragments affect the charge collection. So, we can use MLFC to measure the proton range and energy.

But for carbon beam, the situation is different. High energy charged fragment occur along the beam penetration path in materials. These charged fragments include H, He ,Li ,Be and B. Those fragments will continue move forward and will also be collected by charge meter as well as primary carbon particle. Its will have an affection on charge collection. Fortunately, the peak of these charged fragments are near the Bragg peak.

Differential Fluence v. Depth of Proton Beam

For proton therapy beam, the range distribution can be described by Gaussian function [14-16]

$$R_0(x) = I_0 \exp\left(-\frac{(x-R_0)^2}{2\sigma_0^{\ 2}}\right) \tag{1}$$

Where I_0 is beam total charge, R_0 is beam range and σ_0 is the sigma of the Gaussian range straggling. The differential charge distribution as a function of depth in copper of a 70 MeV proton beam is simulated by Fluka (Fig. 1). The

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basic parameters and process is described below. The density of the copper is 8.9 g/cm^3 and the total thickness of the copper plate is 10 mm. Beam fluence at each depth are calculated by USRTRACK card and the differential charge (deposited charge in each layer) can be derived by subtraction. Gaussian fitting of the differential fluence curve shows a good fitting. This point confirmed the hypothesis. Beam range given by the fitting result is 7.04 mm, which is consistent with NIST result 7.09 mm. In another words, we can use the maximum position of the differential fluence distribution or deposited charge distribution as the beam range. We also can derive beam energy form beam range.

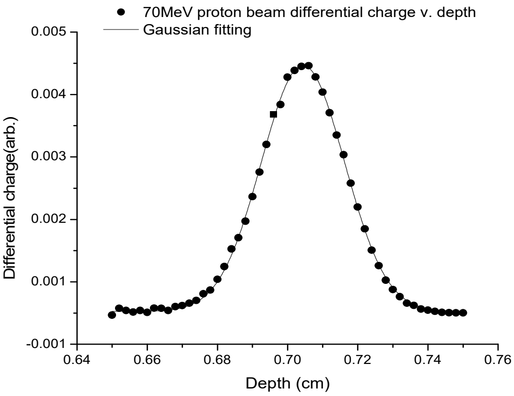

Figure 1: The differential charge distribution as a function of depth of 70 MeV proton beam in copper (points) and Gaussian fitting (solid line).

We also simulated the deposited charge by 250 MeV with 0.5% Gaussian distribution energy spread proton beam in each copper plate of a MLFC (Fig. 2). The MLFC have 64 layer copper plates with 1 mm thickness and 64 layer Kapton insulting films with 50 µm thickness.

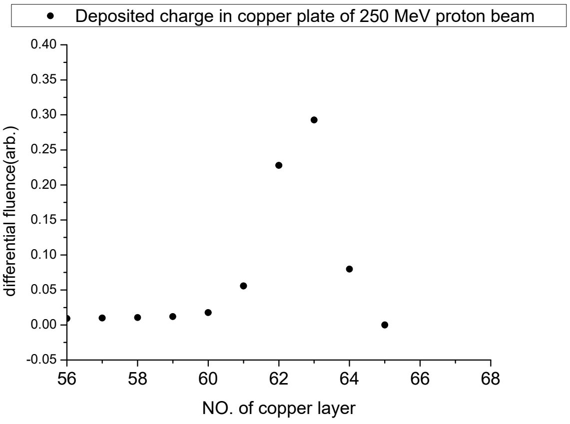

Figure 2: The deposited charge in each layer of 250 MeV 0.5% Gaussian distribution energy spread proton beam.

Deposited Charge v. Depth of Carbon Beam

As analyzed before, there will be many kinds of charged segments produced when carbon beam penetrating material. E. Haettner and H. Iwase et al have studied nuclear fragmentation of 200 and 400 MeV/u ^{12}C ions in water through experiment [17-18]. According their experiments, the amount of charged fragments increase with depth and a maximum is reached around the Bragg peak. Behind the Bragg peak the amount of fragments drops down sharply. As a result, we still can use the maximum position of the deposited charge distribution as beam range. The problem is how large the error introduced.

According their experiment's result, H and He are produced most frequently while the production of heavier fragments (B, Be and Li) is much smaller. For example, the Bragg peak is 25.8 cm for carbon in water. At this depth the yields of production are about 0.76 (H), 0.55 (He), 0.06(Li), 0.03 (Be) and 0.07 (B). Because a H^+ ion and a Li^+ ion contains 1 unit charge. A He^{2+} ion and a Be^{2+} ion contains 2 units charge, and a B^{3+} ion contains 3 units charge. From the perspective of the quantity of electric charge, the yields of production of these five fragment are 0.126 (H), 0.183 (He), 0.01 (Li), 0.01 (Be) and 0.035 (B). In total, the electric charge of fragments is 31 percent of the carbon particles.

Simulation of Deposited charge of Carbon Beam

Firstly, Bragg peak curve of 400 MeV/u carbon beam in water was simulated by Fluka. The simulation result show that the Bragg peak is at 27.35 mm. Deposited charge as a function of depth was also simulated. The maximum of the curve is at 27.34 mm which is equal to the Bragg peak.

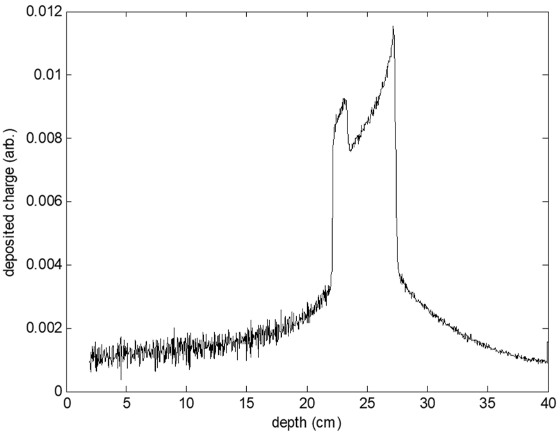

Figure 3: The deposited charge in water of 400 MeV/u carbon beam.

Prototype Design

Our goal is design a MLFC which can cover 80 – 430 MeV/u carbon beam range measurement. Our MLFC (see Fig. 4) consist of 128 layer sheets which include a 29 µm copper foil and a 600 µm FR4 plate which corresponds to approximately 177 µm copper. The diagram of sheet is 90 mm. One sheet is correspond to 206 µm copper. In total, 128 layers sheet are approximately 26.368 mm which equals to the beam range of 286.7 MeV/u carbon beam.

In order to fulfill measurement of 286.7 ~430 MeV/u carbon beam, an absorber system also be designed. The absorber system consists of 2 thick copper whose thickness are 10 mm and 30 mm.

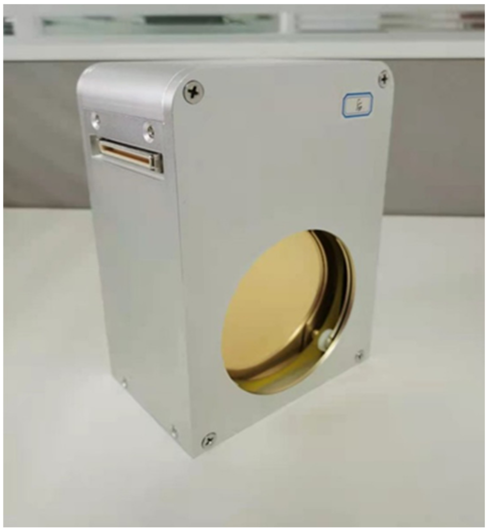

Figure 4: A MLFC prototype consists of 128 layers sheet.

The beam diagnostic system consists of a 128 channel electronics (Fig. 5), a high speed digital I/O module NI 9402, a digital acquisition card NI 9215 and a controller NI cRIO 9064 (Fig. 6). The 128 channel electronics is developed by IMP Electronics Group.

Figure 5: 128 channels electronics.

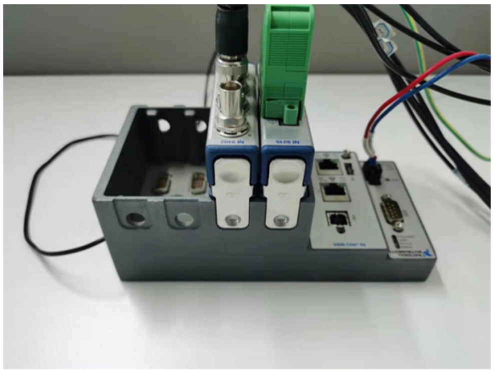

Figure 6: NI 9402, NI 9215 and NI cRIO 9064.

A LabVIEW program was written for controlling and data analysis. And a calibration program is also written. By using Keithley 6221 current source, we calibrate the electronics response at 0.2 nA ~ 2 nA with step 0.2 nA. The calibration coefficient was obtained.

Outlook

Next stage, we plan to do some experiment. And experiment data will be compare with water tank. We find 2 peaks occur in deposited charge distribution curve (see Fig. 3). It will be analyzed by simulation and experiment.

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