ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK036

PROGRESS ON ELECTRON BEAM OPTIMIZATION FOR FLASH RADIOTHERAPY EXPERIMENT AT CHIANG MAI UNIVERSITY

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Abstract

At present, one of diseases that kills many people worldwide is cancer. The FLASH radiotherapy (RT) is a promising cancer treatment under study. It involves the fast delivery of RT at much higher dose rates than those currently used in clinical practice. The very short time of exposure leads to the destruction of the cancer cells, while the nearby normal cells are less damaged as compared with conventional RT. This work focuses on study of FLASH-RT experiment using electron beams produced from the accelerator system at the PBP-CMU Electron Linac Laboratory. The structure and properties of our electron pulses with microbunches in picosecond time scale and macropulses in microsecond time scale match well to FLASH-RT requirement. To optimize the condition for experiment, the electron beam simulations are performed by varying energy, charge and bunch length. The 25 MeV electrons energy before hitting the window for 50 and 100 pC bunch length have a bunch length of 1.16 and 1.97 ps. The transverse rms beam sizes of 50 pC and 100 pC bunch charges have the differences between ASTRA and GEANT4 from 7.90% to 34.0%. The optimized electron beam properties from this study will be used as the guideline for further simulation and experiment preparation.

INTRODUCTION

FLASH radiotherapy (RT) is the current trend option to treat the cancer cell. The concept of fast delivery of radiation or charged particle beam with high dose rate has high efficient capability to kill cancer cells, while the healthy cells nearby are unharmed. This kind of RT using electron beam has been developed in many facilities. In Armenia, there is the Advanced Research Electron Accelerator Laboratory (AREAL), which focuses on ultra-short electron beam pulses in energy range of 2 - 5 MeV. They study the effect of the dose rate in DNA by investigating the damage and repair process in vitro experiment [1, 2]. In Germany, there is the Helmholtz Institute Jena (HI Jena), which studied about the radio-biological effect when irradiating the electron beam on tumour cells. The electron pulses have energy in a range of 2 - 45 MeV [3, 4]. In 2016, they used the laser-based accelerator to produce electron pulses with ultra high dose rate. They compared the electron beam irradiation with high and low dose rate to study the effect in the normal cells [5].

The accelerator system at the PBP-CMU Electron Linac Laboratory (PCELL) has potential to produce electron beam with properties suitable for studying the RT with high dose rate. At our facility, electrons are generated from a thermionic cathode RF-gun. Then, they are accelerated through the gun cavities and travel to the alpha magnet. After exiting the alpha magnet, the electron bunches are accelerated in the RF-linac to reach maximum energy of up to 25 MeV. The electron beam properties including energy of 6 - 25 MeV, macropulse of 1 - 4 μs , microbunch of 0.3 - 1 ps, variable high current, and low emittance are well suit for FLASH-RT experiment. The experimental set up for the cell irradiation will be placed at the end of the beam dump as shown in Fig. 1. The computer simulations are used to study the dynamics of the electron beam. The aim of this work is to optimize the electron beam to reach the FLASH-RT conditions. The preliminary results from the simulations using ASTRA and GEANT4 program are presented in this work [6, 7].

METHODOLOGY

The research team at PCELL plans to study the FLASH-RT experiment by using electron beams with high dose rate ($\geq$ 40 Gy/s), which is defined for the FLASH-RT [8]. To reach the FLASH conditions, the electron beam has to be optimized. The electron beam dynamic simulation was performed by using a computer program ASTRA [6]. The space charge effects were included in this investigation. Electrons were generated in the RF-gun with 4 million macro-particles. The RF-wave separates the macroparticles into groups called microbunches. These electron bunches travel through the alpha magnet with a fixed gradient of 300 G/cm. The energy slit installed inside the vacuum chamber of the alpha magnet was used to choose the charge of electron bunch

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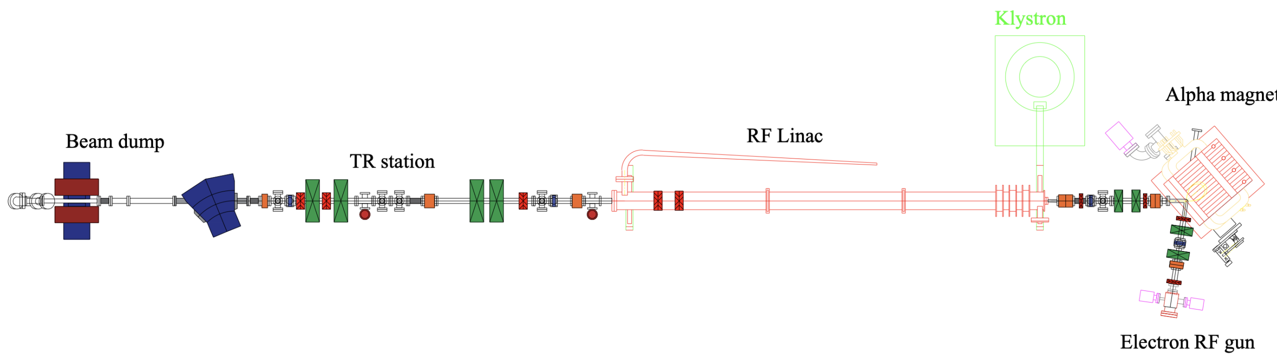

Figure 1: The layout of the PCELL accelerator system.

which are 50 pC and 100 pC in this study. Then, the electron bunches are accelerated in the linac to reach the energy of up to 25 MeV. The trajectory and transverse size of electron beam are controlled by using steering and quadrupole magnets to reach the beam dump. The cell irradiation set up will be placed in air downstream the titanium window (Ti-window). However, ASTRA program cannot simulate the interaction between electrons and matter. Therefore, the GEANT4 software was used to perform Monte Carlo simulation by using the electron beam input from ASTRA output simulated through the Ti-window. This works started with comparison of electron beam transverse distributions between ASTRA output and GEANT4 input without hitting the Ti-window. This was conducted in order to ensure that the transfoemation of the electron beam distributions ASTRA output to GEANT4 input are identical. Then, the GEANT4 simulation was performed for injecting electrons to hit the Ti-window and observing the transverse distribution of electron beam at three positions downstream the Ti-window.

RESULTS AND DISCUSSION

In the simulation, we considered a single particle microbunch by assuming that all bunches have indistinguishable properties. The electrons beam with a bunch charge of 150 pC and an average energy of 2.24 MeV is produced from the RF-gun. The electron beam with bunch charges of 50 and 100 pC were chosen by using low energy slit in the alpha magnet vacuum chamber. The beams with both two bunch charges are then accelerated to gain the energy up to 25 MeV in the RF-linac. The 3D mesh in Cartesian coordinates were used in ASTRA simulation. The optimization of mesh number was done. It was found that the proper numbers of mesh in x,y and z axis are 32,32,64 and 32,32,32 for the bunch charge of 50 and 100 pC, respectively. These values were used to simulate the beam to the end of the beam dump. The simulation results show that the bunch length of the beam with 50 and 100 pC before reaching the beam dump are 1.16 and 1.97 ps, respectively.

The output particle distributions from ASTRA simulation were transformed to be the input particle distribution for comparison of the transverse beam size and distributions of ASTRA output and GEANT4 without hitting The Ti-window are shown in Table 1 and Fig. 2. The transverse rms beam sizes of 50 pC electron bunch have the differences between ASTRA and GEANT4 of 7.90% and 25.2% for x and y-axis, respectively. For the 100 pC bunch charge, the differences of x and y rms beam size are 14.7% and 34.0%. The beam transverse distributions in Fig. 2 show that the higher charge causes more beam divergence, causing by space charge effects. Therefore, the transverse beam size of 100 pC bunch charge has the difference between the particle distributions obtained from ASTRA and GEANT4 more than the 50 pC case.

Table 1: Transverse Beam Size of Electron Bunches for ASTRA Simulation Output and GEANT4 Input

Beam size (mm)	ASTRA	GEANT4
	50 pC bunch charge	
x rms	2.16	2.00
y rms	3.25	2.52
	100 pC bunch charge	
x rms	2.05	1.77
y rms	3.01	2.13

Then, the Ti-window was include in the GEANT4 simulation. The position of the scorer was varied by 0.2, 0.6 and 1.0 m apart from the Ti-window exit. The transverse beam distributions after the beam collision with the Ti-window were studied and they are shown in Fig. 3. The results show the scattering of electrons after the collision. The transverse beam sizes for 50 pC bunch charge are 3.8, 5.8 and 7.1 mm at the above mentioned scorer positions respectively. For the 100 pC bunch charge, the transverse beam sizes are 3.8, 5.8 and 7.2 mm at three positions, respectively.

SUMMARY AND OUTLOOKS

The space charge effects together with electron scattering cause the divergent of electron beam after hitting the Ti-window. The beam distributions after collision Ti-window have a hole at the center of the bunch due to the inhomogeneous transverse energy of electrons. The electrons with

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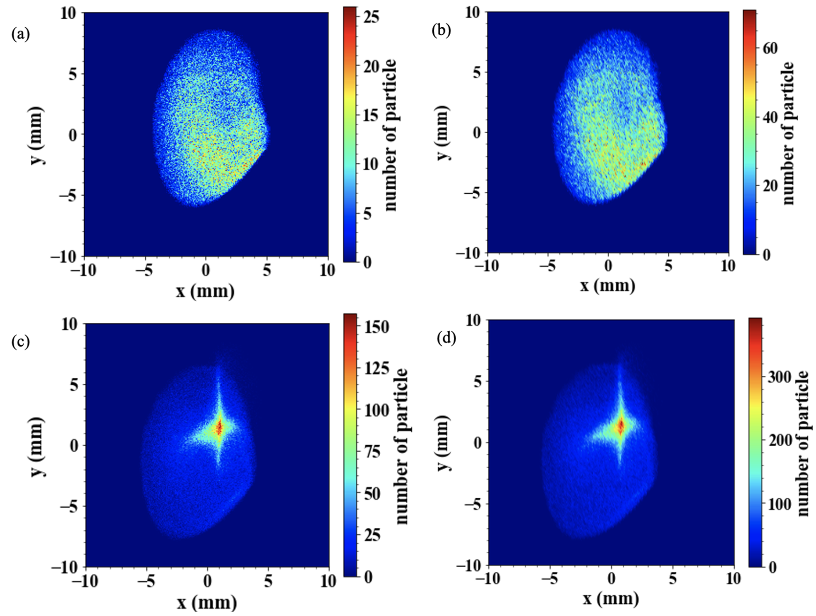

Figure 2: The transverse distributions of electron beam with energy of 25 MeV obtained from ASTRA simulation outputs (a and c) and GEANT4 input (b and d). The first row distributions are for 50 pC bunch charge and the second row distributions are the 100 pC bunch charge.

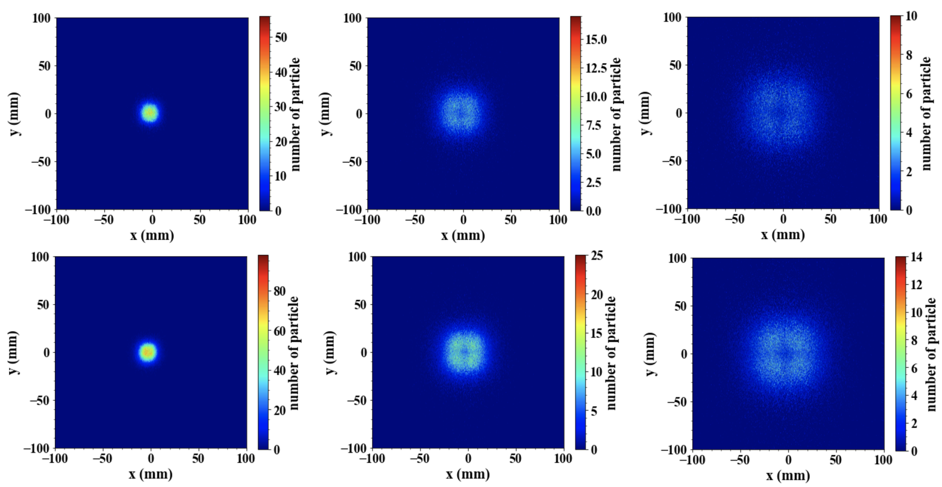

Figure 3: The transverse beam distributions for 50 pC (first row) and 100 pC (second row) at the position 0.2,0.6 and 1 m apart from the Ti-window.

lower energy stay at the center of the beam. Therefore, some of them were stopped at the Ti-window and cannot travel further. Some quadrupole magnets will be installed downstream the Ti-window to control the transverse beam size and the density of electrons per irradiation area. The optimization of quadrupole gradient is necessary. Further study to design the experimental station, the electron beam diagnostics and the dose measuring system will be performed in the future.

ACKNOWLEDGEMENTS

This research has received support from Chiang Mai University and the NSRF via the Program Management Unit for Human Resources Institutional Development, Research and Innovation [grant number B16F630068]. K.Kongmali would like to acknowledge the scholarship support from Science Achievement Scholarship of Thailand (SAST).

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