ISBN: 978-3-95450-265-3 doi:10.18429/JACoW-SAP2023-TUPB026

DESIGN OF A SYNCHROTRON FOR PROTON FLASH RADIOTHERAPY BASED ON FAST VARIABLE-ENERGY BUNCH SPLITTING*

Y. Li, H. J. Yao, S. X. Zheng†, Q. Z. Xing‡, X. W. Wang
Key Laboratory of Particle & Radiation Imaging, Ministry of Education, Beijing, China
†also at Laboratory for Advanced Radiation Sources and Application,
Tsinghua University, Beijing, China
‡ also at Department of Engineering Physics, Tsinghua University, Beijing, China

Abstract

Ultra-high dose rate (FLASH) radiotherapy not only guarantees effective tumor treatment but also greatly enhances the protection of normal tissue. Moreover, it is a convenient procedure for tumor patients that has enhanced the benefits provided by medical institutions. Proton FLASH radiotherapy, which combines the Bragg peak effect of proton spatial dose distribution with the unique temporal effect advantage of FLASH, is an attractive tumor treatment approach. To achieve proton FLASH discrete pencil beam scanning in a 1-L volume, taking into account the 5-mm point interval, 9261 points would need to be irradiated within 500 ms, which is beyond the capability of existing medical devices. To meet these requirements, based on a fast cycle synchrotron with a period of 25 Hz, we simultaneously combined variable-energy, fast splitting, and extraction beam bunches, and proposed a scanning method suitable for continuous variable-energy extraction bunches. The proposed technique meet the requirements of proton FLASH discrete pencil beam scanning within a volume of 1 L.

INTRODUCTION

While ensuring the effect of tumor treatment, FLASH therapy greatly reduces the damage to normal tissue cells [1], and at the same time brings convenience to tumor patients and improves the benefits of medical institutions. Proton FLASH therapy, which combines the Bragg peak effect advantage of spatial dose distribution and the unique time effect advantage of FLASH therapy, is a very attractive tumor therapy. The ultra-high dose rate (>40 Gy/s) and very short treatment time (usually less than 500 ms) in the target area of FLASH therapy impose high requirements on the accelerator outlet beam intensity and energy transformation time. Synchrotron has the advantage of active energy regulation. Using proton synchrotron in FLASH therapy combined with spot scanning irradiation therapy with high beam utilization rate is expected to meet the requirements of dose rate and irradiation time in the target area.

Due to the high requirements of proton FLASH therapy for dose rate and treatment time, only some medical institutions have conducted proton radiotherapy based on small volume or fixed energy penetration irradiation on cyclotrons. Some preliminary results of these experiments have shown the effect of FLASH therapy, but further research is needed in more functional proton radiotherapy equipment. At present, cyclotrons are mainly used in medical institutions around the world. However, cyclotrons have low energy regulation speed, high beam loss and great influence on beam quality, which is not conducive to the treatment of tumors with large depth distribution. Synchrotron has the advantage of active energy regulation, which can shorten the energy regulation speed and ensure the beam quality, and has certain advantages in the application of FLASH therapy. However, some key problems still need to be solved in the application of proton synchrotron in FLASH therapy.

KEY ISSUES AND CHALLENGES

Proton FLASH therapy is a kind of ultra-high dose rate radiotherapy. The average dose rate is not less than 40 Gy/s and the total irradiation time is in the order of hundred milliseconds. For the pencil beam scanning method, the average dose rate in the target scanning process can be calculated according to the dose sum of each scanning point and the total scanning time:

$$\dot{D} = \frac{D}{T} = \frac{\sum_{i=1}^{n} D_i}{\sum_{i=1}^{n}(T_{deli,i} + T_{scan,i}) + \sum_{j=1}^{m} T_{energyswitch,j}} \tag{1}$$

where, $\dot{D}$ is the dose rate ; D is the dose sum of each scanning point; T is the total treatment time; there are n scanning points and m energy switching processes; D_i is the dose of each scanning point; $T_{deli,i}$ and $T_{scan,i}$ are the beam delivery time and scanning time of each scanning point, respectively; and $T_{energyswitch,i}$ is the time of each energy switching.

To improve the average dose rate, it is necessary to increase the number of particles reaching the target area during the treatment time, and to shorten the delivery time, energy switching time, and scanning time. In the volume of 1 L, to meet the minimum dose rate requirement of 40 Gy/s for proton flash therapy, the number of particles required for 100 ms was 3.8×10^{11}[2]..

At present, medical institutions providing radiation therapy around the world mostly use cyclotrons to extract beams of fixed energy, and irradiate in the target area after energy regulation. Energy regulation with a range shifter

* Work supported by National Natural Science Foundation of China (No. 12075131).
† zhengsx@tsinghua.edu.cn
‡ xqz@tsinghua.edu.cn

ISBN: 978-3-95450-265-3 doi:10.18429/JACoW-SAP2023-TUPB026

has the problem of producing a large number of secondary particles and large residual radiation. The multi-energy slow extraction method of the synchrotron provides a new idea to solve the above problems. By changing the energy of the particles at the right time during the extraction process, the extracted particles will deposit the dose at different depths in the lesion area due to different energy, so that the dose can be deposited at different depths of the target area without the need of energy reduction device. In order to give full play to the variable energy advantages of the synchrotron, if the multi-energy fast extraction can be realized, it will further shorten the treatment time, if the beam bunch can be divided into several small beam bunches in advance in the ring, it will greatly improve the convenience of multi-energy fast extraction, and at the same time provide the possibility for the application of back-end extraction beam in radiotherapy with three-dimensional point scanning.

To perform spot scan FLASH therapy on a 1 L (10 cm×10 cm×10 cm) tumor within 500 ms, a total of 9261 spots[3] would be scanned with an average scan interval of 54 µs per spot at a dot interval of 5 mm. 21 energy layers are required, and the switching time between adjacent energy layers is required to be <25 ms. In order to shorten the time interval of point scanning during flash therapy, we used square wave pulse voltage to split the bunch in the synchrotron. By adjusting the pulse voltage to control the number of particles in the small beam cluster, we avoided the waiting time to turn off the beam according to the dose feedback on the target. In the follow-up study, we improved the beam bunch splitting method to meet the requirements of point scanning interval of FLASH therapy. In order to shorten the time to adjust the energy, the energy is adjusted by a square wave pulse voltage in the time interval of generating small beam bunches, and finally the variable energy beam splitting is realized. Combined with the oblique scanning method for continuous variable energy beam splitting, the variable energy scanning irradiation can be realized, so as to meet the requirement of variable energy during FLASH therapy.

DESIGN OF A SYNCHROTRON

To reduce the required number of particles in a synchrotron duty cycle, a 25-Hz fast-cycle synchrotron with a period of 40 ms can be used. This allows for multiple cycles in a single FLASH treatment time (e.g., 500 ms), thereby reducing the need to store a high number of particles in one cycle. The rising stage of the main magnet of the fast cycle synchrotron generally produces a sinusoidal magnetic field waveform, and there is no platform for fixed energy extraction, as Fig. 1 shows. In one working cycle, half of the period of 40 ms is used for demagnetization. To make full use of the cycle, the time interval of the scanning points is increased as much as possible. To provide more time for beam splitting, it is necessary to combine the beam splitting and extraction process with the rise and fall of the magnetic field to realize the continuous variable-energy beam splitting and extraction process.

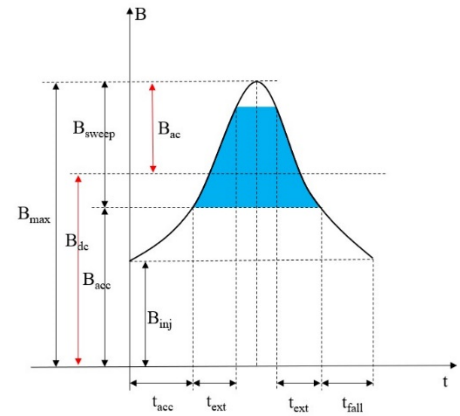

Figure 1: The intensity waveform curve of the main magnet.

In a fast cycle of 40 ms, the rising stage of the main magnet lasts for 20 ms. The waveform expression of the main magnet strength is as follows:

$$B = B_{dc} + B_{ac} = \frac{(B_{\max} - B_{inj})}{2}\sin(2\pi f(t - t_0)) + \frac{(B_{\max} + B_{inj})}{2} \quad (2)$$

B_{dc} represents the DC part of the main magnet waveform, B_{ac} represents the sinusoidal part of the main magnet waveform, B_{max} represents the maximum value of the main magnet waveform, B_{inj} represents the strength of the magnetic field corresponding to the injected energy, and f is the frequency of the sinusoidal waveform. For a fast cycle synchrotron with a period of 40 ms, f can be set as 25 Hz, and t is the time. t_0 represents the amount of translation of the sinusoidal waveform on the time axis, which is negative when translated to the right and positive when translated to the left. Generally, the strength of the main magnet at $t = 0$ is minimized, i.e., the sinusoidal waveform is translated to the right on the time axis by a 1/4 cycle.

Figure 2 shows the waveform distribution of the barrier bucket. V2 and V4 form a pair of potential well voltages that are used to constrain the particles of the main beam bunch. A low V2 amplitude is set to ensure that some particles overflow from the main beam bunch area to the left. The particles entering the left phase area increase their momentum dispersion under the action of the larger voltage of V1, accelerating the phase shift speed in the left phase area. The momentum dispersion of particles on the left side does not change within the phase range covered by the V3 voltage. The protruding part of V3 on the left side prevents the momentum dispersion of the overflow particles from being substantially deviated due to the change in the energy of the main beam bunch. After the particles overflow to the left, the kicker is applied in a certain phase range to kick these particles out of the circulating beam. This is combined with the back-end electrostatic septum (ES), magnetic septum (MS), and other extraction devices to realize the extraction of this part of the particle beam. The single-turn phase shift of the particle beam in the longitudinal direction is determined as follows:

$$V_{\varphi} = 2\pi\eta\delta. \quad (3)$$

V1 can effectively improve the phase shift speed by increasing the momentum dispersion of particles entering the left region. In a short time (tens of μs), the particle phase shift can cover the phase region kicked out by the kicker, so that the particles can fill the phase region again, thus ensuring the continuity of the split beam bunch. In this process, V3 remains open, and the split beam is carried out in the process of energy switching. The time interval of the kicker kicking out the bunch is the time required for particles to make up for the kicker kicking them out of the phase area. If the required number of turns is n and the period is T, then the time interval of the kicker kicking out the bunch is:

$$t = n \cdot T_0 = \frac{\varphi}{2\pi\eta\delta} \cdot T_0 = \frac{\frac{T_{kicker}}{T_0} \cdot 2\pi}{2\pi\eta\delta} \cdot T_0 = \frac{T_{kicker}}{\eta\delta} \quad (4)$$

where, T_{kikcer} is the pulse duration of the kicker, which together with η and δ determines the time interval required for kicking out the bunch.

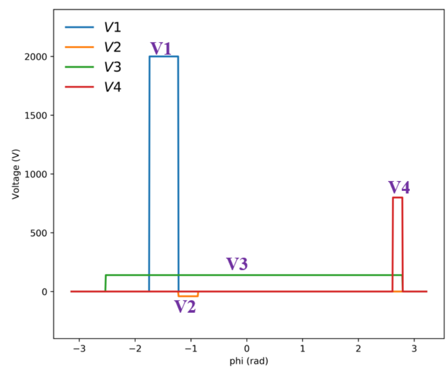

Figure 2: The waveform distribution of the barrier bucket.

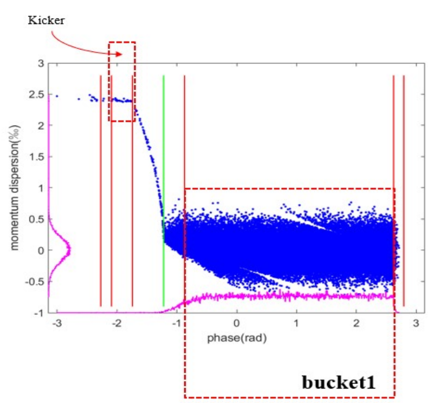

Figure 3: The longitudinal phase space of the bunch to be extracted.

The longitudinal phase space during the rapid bunch splitting process is shown in Fig. 3. The momentum dispersion range of the beam before bunch splitting is ± 0.6‰. During the bunch splitting process, the particles enter the left side from the bucket1 region, and the momentum dispersion of the particles increases to 2.5‰ under the action of V1. At Tkikcer = 30 ns, the time interval for kicking out the bunch is t = 20 μs, that is, the fast splitting of bunches can be realized.

The extraction process takes "kicker + electrostatic deflector + Lambertson magnet" to complete as Fig.4 shows. kicker first acts on particles of a specific phase to realize the pre-separation of the particles to be extracted and the circulating beam. Kicked particles enter the diaphragm of the electrostatic deflector and are deflected by the electrostatic deflector into the Lambertson magnet, thus entering the transport line for transmission to the target station.

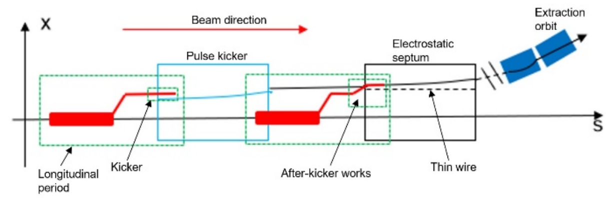

Figure 4: The schematic diagram of the extraction process.

A fast cycle synchrotron based on the existing component layout of the XiPAF (Xi 'an 200 MeV Proton Application Facility) can be combined with the rapid variable-energy bunch splitting and extraction methods described above to achieve improved outcomes. The key parameters of synchrotron scheme design are shown in Table 1.

Table 1: The Key Parameters of the Synchrochon

Parameter	Value	Parameter	Value
Ion type	Proton	Magnetic Rigidity	0.38~2.43T·m
Circumference	30.9m	Particle Number	≥3.88e11
Energy (Min.)	7 MeV	Energy (Max.)	70~250MeV
Frequency (Min.)	1.2MHz	Frequency (Max.)	6.0MHz
Operating Frequency	25Hz	Time per Cycle	40ms

CONCLUSION

Aiming at the needs and challenges faced by the application of proton synchrotron in the pencil beam scanning FLASH therapy scenario, this paper proposes to alternate the fast beam bunch splitting and extraction processes in the continuous energy transformation process of the fast-cycle synchrotron, so as to realize the beam bunch with continuous energy sweeping at the exit of the accelerator, so as to shorten the energy transformation time during the pencil beam scanning therapy, improve the dose rate on the target, and finally meet the requirements of the FLASH therapy for dose rate and total treatment time.

REFERENCES

[1] J. Bourhis, W.J. Sozzi, P.G. Jorge, et al., “Treatment of a first patient with FLASH-radiotherapy”. Radiother. Oncol. vol. 139, p. 18-22, 2019. doi: 10.1016/j.radonc.2019.06.019

[2] S. Jolly, H. Owen, M. Schippers, et al., “Technical challenges for FLASH proton therapy”. Phys. Med. vol. 78, p. 71−82, 2020. doi: 10.1016/j.ejmp.2020.08.005

[3] E. Kanouta, J.G. Johansen, G. Kertzscher, et al., Time structure of pencil beam scanning proton FLASH beams measured with scintillator detectors and compared with log files. Med. Phys. vol. 49, p. 1932-1943, 2022. doi: 10.1002/mp.15486