HOLLOW BUNCH METHOD FOR IMPROVED SPOT DOSE ACCURACY IN 3D PBS PROTON FLASH[*]

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Abstract

A longitudinal localized kick-driven fast extraction technique has been employed to enable three-dimensional (3D) proton pencil beam scanning (PBS) at ultra-high dose rate (FLASH) for large-volume targets. However, it was observed that the longitudinal line density of the proton bunch significantly influences spot dose accuracy. In this study, a hollow bunch method—implemented by using two harmonic waves to manipulate the longitudinal phase space—is applied to reduce the line density in the extraction region. The RF parameters are carefully chosen so that the evolution of the phase space satisfies the requirements. Simulations conducted with the SynTrack code demonstrate that this method can effectively reduce the line density in the extraction region, thereby offering the potential to improve spot dose accuracy.

INTRODUCTION

Ultra-high dose rate (FLASH) radiotherapy has become a research hotspot [1] in the field since its ability to reduce normal tissue toxicity while maintaining tumor control was first discovered in 2014 [2]. This effect was initially observed in electron beam radiation and later confirmed with X-rays [3] and proton beams [4]. Several approaches exist to realize proton FLASH delivery, among which three-dimensional (3D) proton pencil beam scanning (PBS) with FLASH delivery is considered the most promising.

For large-volume targets, a delivery scheme in which the scanning layer is aligned parallel to the beam direction has been applied to address the timing limitation of approximately 100 ms [5]. A dedicated rapid cycling synchrotron (RCS) was designed to support this approach. For each scanning spot, a longitudinal localized kick-driven fast extraction technique is employed to facilitate rapid beam extraction during acceleration while maintaining precise control of the spot dose [6]. However, it has been identified that the longitudinal beam line density significantly impacts on the spot dose accuracy, and reducing the line density is a crucial means of improving dose accuracy.

In Ref. [6], the line density was reduced by decreasing the total number of particles stored in the synchrotron. This leads to a trade-off between spot dose accuracy and the irradiated volume size. This paper aims to reduce the longitudinal line density in the extraction region while maintaining the total stored particles by using hollow bunch method.

HOLLOW BUNCH CREATION

The hollow bunch method was initially proposed by CERN to increase the bunch factor at transfer from the PSB to the PS [7]. Reducing the peak current and direct transverse space charge forces leads to less blow-up and lower losses at low energy in the PS.

The basic principle of this method involves using the $h = 1$ and $h = 2$ RF systems to form longitudinal phase space with buckets shown in Fig. 1. Particles are initially distributed inside the large bucket. By manipulating the voltage and phase of the RF system, the large bucket shrinks while the small bucket expands. During this process, particles originally inside the large bucket flow into the newly emerged bucket and the peripheral regions (with lower density) enter the new bucket first, as illustrated in Fig. 2. Consequently, the new bucket region has a lower longitudinal density and can be used as the extraction region to improve spot dose accuracy.

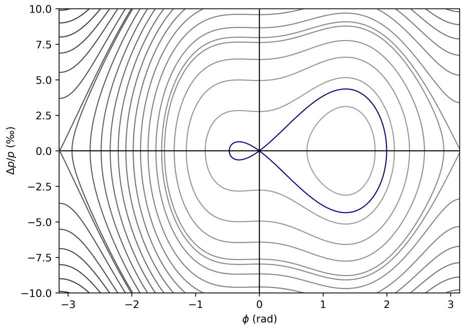
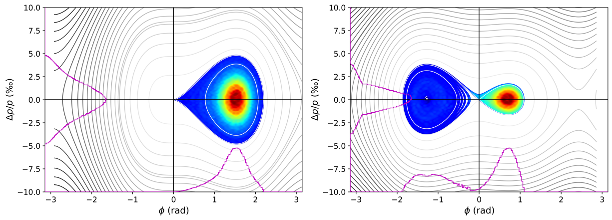


Figure 1: The iso-Hamiltonian map of the longitudinal phase space in hollow bunch method. Particles will move along the iso-Hamiltonian line and the violet contour is the boundary of the stable region (bucket).



(a) (b)

Figure 2: The evolution of particle distribution in the longitudinal phase space in hollow bunch method. (a) there is only one bucket with the second bucket has not been formed; (b) as the original bucket shrinks, the newly formed bucket become larger and is filled with low density particles.

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The waveform of the RF system can be expressed as

$$\begin{aligned} V(t) &= V_1(t)\sin\left(\omega_s t + \phi_{1s}(t)\right) \\ &\quad + V_2(t)\sin\left(2\omega_s t + \phi_{2s}(t)\right), \end{aligned}$$

where ω_s is the angular revolution frequency of a reference (synchronous) particle, and V_1, V_2, ϕ_{1s}, ϕ_{2s} describe the voltages and phases of the RF system.

Unlike the case in Ref. [7], the RF parameters in an RCS must also satisfy the following equation (where B is the magnetic field of the RCS dipole, ρ is the bending radius of the dipole, and C is the circumference of the RCS):

$$V_1(t)\sin\left(\phi_{1s}(t)\right) + V_2(t)\sin\left(\phi_{2s}(t)\right) = \dot{B}(t)\,\rho C.$$

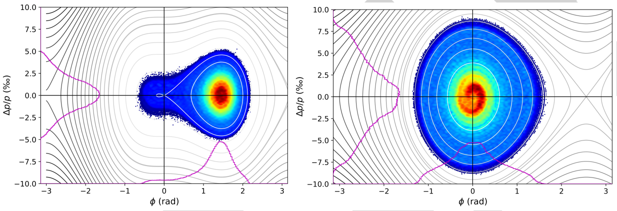
This ensures that the energy increasing of the proton bunch matches the ramping of the magnets.

SIMULATIONS AND RESULTS

Simulation Settings

The simulation was conducted using a high-speed, parallel particle tracking code named SynTrack. Derived from Li-Track [8], SynTrack is a `C++` based synchrotron beam dynamics simulation code designed for high performance. It also employs a symplectic integration algorithm to ensure physical accuracy in long-term tracking.

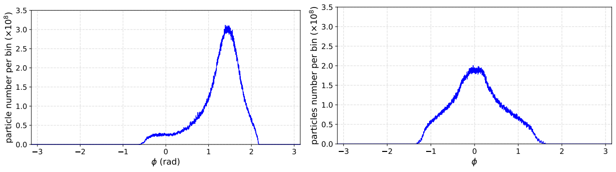
To compare the effectiveness of the hollow bunch method, two simulation setups were simulated: one with the $h = 1$ and $h = 2$ RF systems to form hollow bunch and the other using conventional single-harmonic RF system. The total number of particles stored in the ring before extraction is 1.8×10^{11} with $N_{\mathrm{ext,design}} = 2 \times 10^8$ particles extracted per scanning spot for both settings. Extraction begins when the energy of the proton beam reaches 70 MeV. The phase space and longitudinal line density of the proton beam before extraction shown in Figs. 3 and 4, respectively. It can be seen that the longitudinal line density on the left side is much lower than that in the bunch core, allowing extraction to be applied in this region.



(a) (b)

Figure 3: Longitudinal phase space of the proton bunch before fast extraction. (a) double RF system to form hollow bunch; (b) conventional single RF system.

It should be noted that the initial particle distribution exceeds the bucket in Fig. 3a because the initial longitudinal emittance is larger than the bucket area. Reducing the initial emittance would increase space charge effects, leading to more beam loss.



(a) (b)

Figure 4: Longitudinal line density of the proton bunch before fast extraction with time resolution of 0.1 ns. (a) double RF system to form hollow bunch; (b) conventional single RF system.

The phase space behavior under different RF parameters was carefully studied, and the final chosen parameters are listed in Table 1. The time dependence of the RF parameters $V_1(t)$, $V_2(t)$, $\phi_{1s}(t)$ and $\phi_{2s}(t)$ is shown in Fig. 5.

Table 1: RF Parameters of the Simulation

time	V_1 **[kV]**	ϕ_{1s} **[°]**	V_2 **[kV]**	ϕ_{2s} **[°]**
After Injection	3.1	7.023	−1.5	3.505
5.00 ms	20.0	20.150	−9.5	9.918
8.50 ms	20.0	−12.665	−15.0	−50.000
8.80 ms	20.0	−12.452	−15.0	−50.000
12.80 ms	20.0	70.904	−15.0	55.000

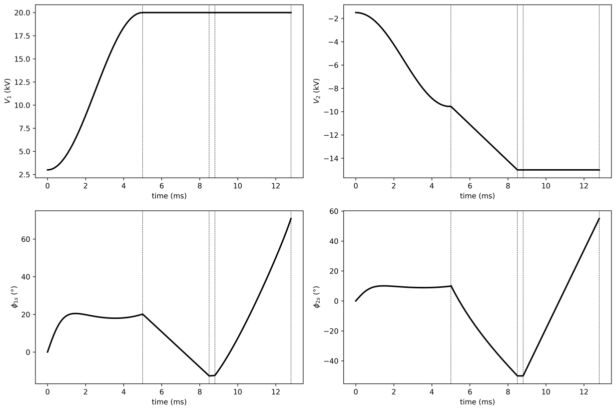


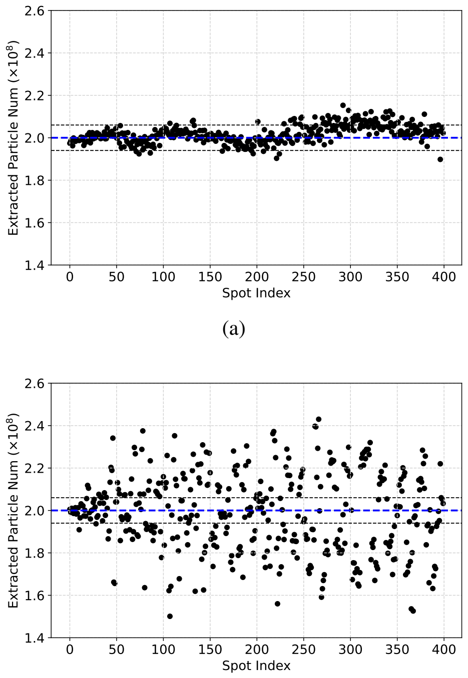
Figure 5: The time dependence of the RF parameters $V_1(t)$, $V_2(t)$, $\phi_{1s}(t)$ and $\phi_{2s}(t)$. The four vertical dashed lines marks the time points of 5.00 ms, 8.50 ms, 8.80 ms and 12.80 ms, respectively.

The time points in Table 1 are chosen as follows:

- After injection till 5 ms: the main function is to cancel the slope of the main RF voltage at the bunch center to lengthen the bunch [9].
- The parameters at 8.5 ms correspond to the phase space shown in Fig. 3a.
- The period from 5 ms to 8.5 ms is a transition phase for adjusting the parameters.
- The 0.3 ms gap after 8.5 ms is used to extract particles outside the bucket Fig. 3a.

- From 8.8 ms to 12.8 ms, ϕ_{1s} and ϕ_{2s} vary with time to shrink the right bucket and expand the left bucket; extraction also occurs during this period.

Simulation Results



(a)

(b)

Figure 6: Results of extracted spot dose accuracy. The blue dashed line is the designed number of particles to be extracted, while the two black dashed lines represent the acceptable error of ±3 % for medical use. (a) double RF system to form hollow bunch; (b) conventional single RF system.

The extracted spot dose accuracy results are shown in Fig. 6. The 400 spots are designed to cover one layer of size $10 \times 10\ \text{cm}^2$ with a spot spacing of 5 mm.

For convenience, we use spot dose error to describe accuracy (a higher spot dose error corresponds to lower accuracy):

$$\text{spot dose error} = \frac{N_{\text{ext,simulation}} - N_{\text{ext,design}}}{N_{\text{ext,design}}} \times 100\,\%.$$

In Fig. 6a, 82 % of the scanning spots have a dose error of less than 3 %, whereas in Fig. 6b, only 26 % of the scanning spots meet this criterion. Therefore, a direct comparison of the results clearly shows that the hollow bunch method greatly improves spot dose accuracy.

DISCUSSION

The clinical criterion requires that more than 95 % of scanning spots have a dose error of less than 3 %, meaning that the results shown in Fig. 6a are still not clinically applicable. To further improve spot dose accuracy, the RF parameters need to be optimized.

As mentioned earlier, the extraction process can be divided into two stages: first, particles outside the initial bucket are extracted (spot index < ~70); second, extraction occurs during the hollow bunch process when particles flow from right to left in the phase space (spot index > ~70). The dose accuracy in the first stage is mainly affected by the injection parameters and the RF parameters before 8.5 ms, while the RF parameters after 8.5 ms only affect the dose accuracy of the second stage.

The difficulty is that simulating one parameter set typically takes several hours, making the optimization process very time-consuming. Our future work will focus on solving this problem to ensure that the spot dose accuracy meets the clinical criterion.

CONCLUSION

In this paper, a hollow bunch method using dual-harmonic RF waves ($h = 1$ and $h = 2$) was applied to reduce the longitudinal line density in the extraction region for proton FLASH PBS delivery. Simulations with the SynTrack code demonstrated that, compared to a conventional single-harmonic RF system, the hollow bunch method significantly improves spot dose accuracy: 82 % of scanning spots achieved a dose error within ±3 %, versus only 26 % for the conventional method. Although the current result does not yet meet the clinical requirement of 95 %, the hollow bunch approach shows clear promise. The extraction process was identified to consist of two distinct stages, each influenced by different RF parameters. Future work will focus on efficient optimization of the RF parameters to further enhance dose accuracy and achieve clinical applicability.

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