Multiple energy extraction experiments at XiPAF synchrotron

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Background

- Multiple energy extraction (MEE) can deliver multiple energy flattops per accelerator cycle, improving treatment efficiency.
- In this process, the extraction efficiency of each flattop and the beam loss during non-extraction times are the key parameters influencing the treatment efficiency.
- Such beam loss is mainly composed of the spill intensity overshoot, which is induced by the emittance growth due to the deceleration.
- So, two new schemes for multiple energy extraction are proposed which can reduce the overshoot while maintain high extraction efficiency.

Two new schemes

- The **separatrix area size** (represented by A) for different energy flattops is the **critical factor** in controlling the overshoot and the extraction efficiency.
- We propose two **new** schemes: **Scheme 3** and **Scheme 4**.

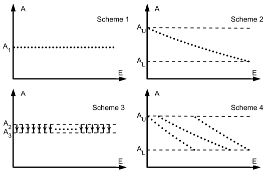


Figure 1: Schematic diagrams of the variation of the separatrix area size with the beam energy E decreased for different schemes. The separatrix area size with high extraction efficiency is limited between A_L and A_U

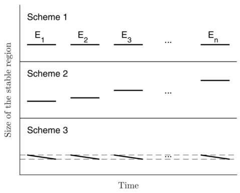


Figure 2: Timing chart of the size of separatrix area (stable region) for different energy flattops for 3 schemes. Scheme 4 is similar to the Scheme 2 but with a larger size variation range.

Multiple energy extraction at XiPAF

- Eexperiments are conducted at the **Xi'an 200 MeV Proton Application Facility (XiPAF)**.
- The multiple energy extraction with 5 and 10 energy flattops has been successfully commissioned at XiPAF successively.

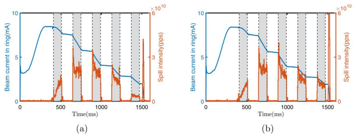


Figure 4: Typical beam current and spill intensity signals for Scheme 1 with 5 energy flattops (from 68 to 60 MeV with a 2 MeV energy interval). The parameters of ES and MS corresponding to a beam energy of 66 MeV in (a) and 62 MeV in (b).

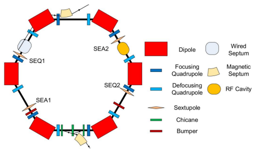
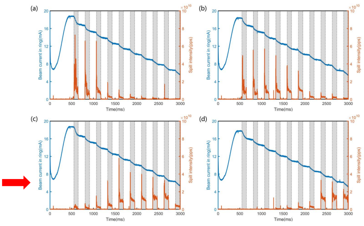


Figure 3: Layout of the XiPAF synchrotron. The XiPAF synchrotron is a 10-200 MeV proton ring of 30.9 m circumference.

Figure 5: Typical beam current and spill intensity signals for Scheme 1 with 10 energy flattops (from 78 to 60 MeV with a 2 MeV energy interval). The parameters of ES and MS corresponding to a beam energy of 78 MeV in (a), 72 MeV in (b), 66 MeV in (c) and 60 MeV in (d).



Experiment 1

- This experiment aims to **verify whether Scheme 3** can reduce the overshoot and matain high extraction efficiency.
- This experiment is **based on the MEE with 5 energy flattops** at XiPAF synchrotron.

Table 1: Experimental conditions.

Experimental conditions.

Parameter	Value
Maximum/Minimum beam energy	68/60 MeV
Beam energy interval	2 MeV
Number of energy flattops	5
Beam extraction time	100 ms
Time for deceleration preparation	20 ms
Time for deceleration	100 ms
Time for extraction preparation	20 ms
Total time for extracted beam energy change	140 ms
Betatron tunes for extraction	(1.682,1.724)
Longitudinal RF voltage for beam acceleration and deceleration	600 V
Longitudinal RF voltage for beam extraction	40 V
Sextupole strength for Scheme 1	42.6 m^{-3}
Sextupole strength for Scheme 2–1 and Scheme 2–2	42.6 m^{-3} for the first flattop, and the sextupole strength after each deceleration is 1/1.03 and 1/1.05 times the previous sextupole strength, respectively.
Sextupole strength for Scheme 3	42.6 m^{-3} at the beginning of the extraction, and the sextupole strength at the end of the extraction is 1.05 times that at the beginning (for all energy flattops).

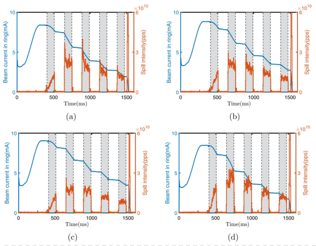


Figure 6: Typical beam current and spill intensity signals for different schemes, the parameters of ES and MS corresponding to a beam energy of 62 MeV. (a) Scheme 1; (b) Scheme 2-1; (c) Scheme 2-2; (d) Scheme 3.

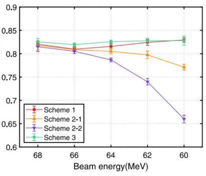


Figure 7: Extraction efficiency vs. beam energy for different schemes, particles extracted in the spill intensity overshoot are excluded when calculating the extraction efficiency.

Conclusion: The overshoot is obviously reduced and the extraction efficiency can be matained high with Scheme 3.

Experiment 2

- This experiment aims to find the **separatrix area size range $[A_L, A_U]$ with high extraction efficiency**. With the range $[A_L, A_U]$, **Scheme 2 and Scheme 4** can be designed reasonably.
- This experiment is **based on the MEE with 10 energy flattops** at XiPAF synchrotron.

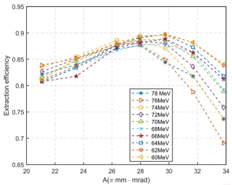


Figure 8: 10 energy flattops' extraction efficiencies at different separatrix area sizes.

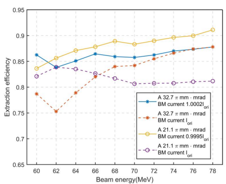


Figure 9: 10 flattops' extraction efficiencies when the separatrix area size is 21.1 and 32.7 π mm · mrad. The bending magnet current is optimized to improve the efficiency.

Conclusion:

- The extraction efficiencies of 10 flattops are mostly over **85%** when the A is **21.1** and **32.7** π mm · mrad
- The separatrix area size range **[21.1, 32.7]** π mm · mrad will be used for the **designs** of Scheme 2 and 4.

Discussion:

The range above **may be larger** with **extraction extraction bump magnets installed** and **more commissioning time**.

Beam loss index and the evaluation model

- To compare different schemes, a **beam loss index** is defined and a **simple evaluation model** established.

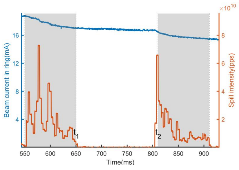


Figure 10: Partial enlarged view of Fig. 5(a) between 550 and 950ms. t_1 represents the first flattop ending time and t_2 represents the second flattop beginning time.

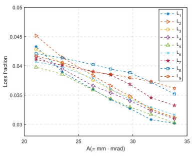


Figure 11: A preliminary experimental observation of the variation of $L_{1\sim9}$ with A based on Scheme 1.

We define the **loss fraction L_1** between t_1 and t_2 as follow,

$$L_1 = \frac{I_{DCCT}(t_1) - I_{DCCT}(t_2)}{I_{DCCT}(t_1)} \qquad (1)$$

The phenomenon that the **loss fraction depends not only on** the separatrix area size variation percentage but **also on** the **separatrix area size itself** should **be paid attention to** in the 4 schemes' designs.

Assuming that the total number of particles in the ring before extraction is N_0, the treatment plan requires total M energy flattops and the number of particles required for each scanning layer is same and set as n. The loss fraction L of each flattop is considered to be same for simplicity and same consideration for the extraction efficiency η. Then we can get the number of remaining particles $N(m)$ at the beginning of the m-th (m>1) flattop as flollow:

$$N(m) = \left\{ \underbrace{\left[\underbrace{(N_0 - \frac{n}{\eta})(1-L)}_{m=2} - \frac{n}{\eta} \right](1-L)}_{m=3} \right\} - \frac{n}{\eta} \ldots = N_0(1-L)^{m-1} - \frac{n}{\eta}\frac{1-(1-L)^{m-1}}{L}(1-L) \qquad (2)$$

What we are concerned about is the number of layers m_{ac} that can be irradiated in an accelerator cycle, and it is defined as follow:

$$m_{ac} = m_{\max} - 1 + \frac{N(m)\eta}{n}$$

Finally, the relationship between m_{mc} and L can be obtained, through which the influence of L can be evaluated quantitatively.

Experiment 3

- This experiment aims to **compare the loss fractions of 4 schemes**.
- This experiment is **based on the MEE with 10 energy flattops** at XiPAF synchrotron.

Separatrix area size designs of four schemes:

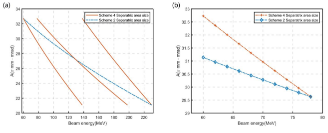


Figure 11: Separatrix area size A vs. beam energy for Scheme 2 and 4: (a) actual needed design within 230~60 MeV; (b) actual used design in the experiment. Scheme 2's separatrix area size is translated down to ensure that the initial separatrix area sizes of the two schemes are same.

Scheme 1: The initial separatrix area size of Scheme 2 and 4 is 21.1 π mm·mrad, so for **Scheme 1**, each flattop's separatrix area size is set to **21.1 π mm·mrad**.

Scheme 3: For **Scheme 3**, each flattop's separatrix area size **shrinks from 21.1 π mm·mrad to 19.1 π mm·mrad** (sextupole strength increased to 1.05 times the initial strength) during extraction.

Eeperiment result:

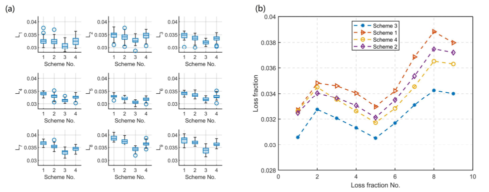


Figure 12: Figures used to compare 4 schemes' loss fractions: (a) a diagram shows how $L_{1\sim9}$ differ based on different schemes; (b) 4 schemes' average loss fractions.

Conclusion:

- From Fig. 12(a), there is a clear trend that **Scheme 3 is better than Scheme 2** and **Scheme 2 is better than Scheme 1**. **Scheme 4** seems to be **not better than Scheme 3** and **a little better than Scheme 2**.
- In Fig. 12(b), it is obviously that the loss fractions of **Scheme 3** are minimum and about **0.002** smaller than **Scheme 4**. The differences between the **other three schemes** are about **0.001~0.002**, with Scheme 4's loss fractions the smallest and Scheme 1's loss fractions the largest. The differences of L_8 between Scheme 3 and Scheme 1 can even reach to **0.005**.

Discussion:

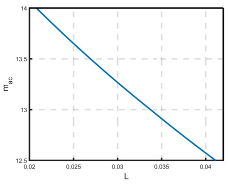


Figure 13: The number of layers mac that can be irradiated in an accelerator cycle vs. loss fraction L.

The parameters' values used in Fig. 13:

- In Eq. (2), N_0 and η are the accelerator related parameters and set to **1 × 10^{11}** and **90%** close to the actual treatment situation.
- Treatment plan and the volume of the tumor decide the parameter n, for example, we assume that a dose of 2 Gray is delivered to a 10 × 10 × 10 cm^3 volume which lies from 10~20 cm deep within another larger water volume, this corresponds to **1.9 × 10^{11}** protons. For the 10 × 10 × 10 cm^3 treatment plan, the number of layers M is **34**, so n is **5.59 × 10^9**.

- The loss fraction differences between different schemes are within **0.005**, so the layer differences in an accelerator cycle between different schemes are estimated within **0.5 layer**.
- The actual treatment time may be reduced about **4% ($\frac{0.5}{13}$)**. This benefit **may be limited** and not obvious since the number 4% itself is indeed a bit small.
- From the aspect of the cost of extra hardware, Scheme 1 and Scheme 4 require no extra hardware cost compared with Scheme 2 while the **Scheme 3 may need an extra hardware cost** to control the sextupole magnet current change rate.
- From the aspect of the **cost of beam commission time**, the ranking from **less to more** is Scheme 1, Scheme 3, Scheme 2 and Scheme 4 according to the complexity of four schemes.
- The loss fraction and m_{ac} generally **decrease as the cost increases**. So, there is no one ideal optimal scheme. **Different schemes are suitable for different circumstances**.
- In situations where such beam loss is acceptable, **Scheme 1** with the **lowest cost** may be a better choice actually.