Extraction Study of High-Temperature Superconducting Skeleton Cyclotron (HTS-SC) for BNCT and Radioisotope Production

H. W. Koay†, M. Fukuda, H. Kanda, T. Yorita
Research Centre of Nuclear Physics, Osaka University, Japan

Abstract

This work discusses a preliminary design as well as the beam dynamics of the extraction of a High-Temperature Superconducting Skeleton Cyclotron (HTS-SC). In previous works, HTS-SC was proposed to serve as a compact and high-current accelerator providing 50 MeV H^+ beams required by Boron Neutron Capture Therapy (BNCT) as well as radioisotopes production in a hospital environment. In order to supress the significant Lorentz stripping effect under a relatively high magnetic field (>2.4 T), H^+ beam was adopted, together with an electrostatic deflector extraction in HTS-SC. However, small final-turn separation and significant space charge effect of such a compact machine remains as a challenge to achieve a high extraction efficiency. Therefore, in order to improve the extraction efficiency of HTS-SC, the beam loss upon colliding with the septum or deflector is minimized by performing an extensive extraction beam dynamics. On top of this, both resonant (precession) and resonant-free (brute-force) extraction are also considered in order to determine the most efficient system in providing extracted beam with desired quality.

INTRODUCTION

In accordance with the need for an in-hospital multi-purpose cyclotron for BNCT and the production of medical radioisotopes for diagnostic/therapeutic purposes, a high-temperature superconducting skeleton cyclotron (HTS-SC) was proposed [1]. A schematic showing the proposed purposes of HTS-SC is shown in Fig. 1. As a hospital-friendly device, HTS-SC is a compact ironless skeleton cyclotron adopting high-temperature superconducting coils in order to guarantee a high-intensity beam with a better stability and reproducibility.

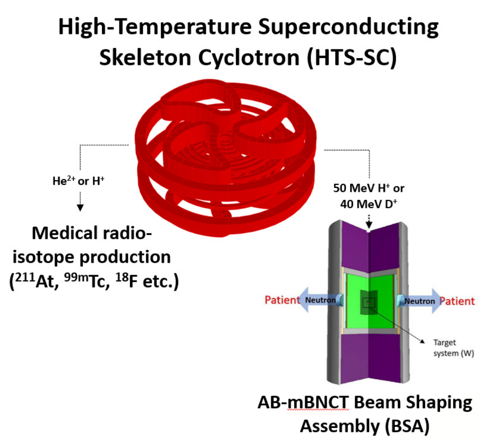

Figure 1: Schematic of the proposed HTS-SC and its application for AB-mBNCT as well as radioisotope production.

The proposed HTS-SC is an air-core K-80 cyclotron with a small extraction radius of 40 cm for multiple-ion beams. It consists of a series of combination of circular high-temperature superconducting coil (HTSC). These HTSC include 3 sector coils (SC) with a maximum spiral angle of 40°, 1 circular main coil (MC) of 55 cm radius, 10 small trim coils (TC) of varying radius from 5 cm to 50 cm and 2 background-stray coil (BC) at 80 cm.

As the main ion source needed for BNCT neutron beam production, the extraction of high-intensity H^+ beam at 50 MeV remains as a challenging task. Electrostatic extraction has the simplest working principle and easy-adjustment. Conversely, it is also widely known for problems such as heat-deposition and radiation of the electrostatic deflector (ESD) in a compact cyclotron due to a small final-turn separation. Thus, this work intend to study the feasibility of electrostatic extraction with the implementation of harmonic coils to improve the final-turn separation, aiming to improve the extraction efficiency as well as the extracted beam quality.

MATERIAL AND METHOD

Turn-separation and resonances

The turn separation of particles in a cyclotron is governed by its natural radial gain due to acceleration and radial oscillations around the equilibrium orbit. Due to the compactness and relatively high magnetic field of HTS-SC, the turn-separation due to acceleration is small. For instance, taking an energy gain per turn of 320 keV and an extraction radius of 40 cm at T=50 MeV, the final turn separation (ΔR) is approximately 1.28 mm. This is insufficient to cleanly separate even a small beam of radial size of 1 mm.

Thus, in order to improve ΔR, harmonic coils (HC) are used to create first harmonic bumps that generate radial coherent oscillation. When the oscillation crosses or approaches integer or half-integer resonances, the oscillation amplitude increases significantly. We can estimate this amplitude by the taking the equation of motion as

$$\frac{d^2x}{d\theta^2} + \nu^2 x = R\frac{\Delta b_1}{B}\cos\theta \quad (1)$$

Assuming the distortion results in a closed orbit oscillation, the particular solution of x is given as

$$x_p = R\frac{\Delta b_1}{B}\frac{1}{\nu^2-1}\cos\theta \ , \ \nu \neq 1 \quad (2)$$

$$x_{max} = \pi R\frac{\Delta b_1}{B}\frac{1}{\nu_r^2-1} \quad (3)$$

Equation (2) is the simplified solution for precessional extraction (PE). The maximum radial separation can be further reduced to Eq. (3). On the other hand, if Eq. (1) has an open orbit solution, the oscillation amplitude is reduced to Eq. (4) with a maximum ΔR as described in Eq. (5).

$$x_p = R\frac{\Delta b_1}{B}\frac{\theta}{2\nu}\sin\nu\theta\,,\ \nu = 1 \tag{4}$$

$$x_{max} = \pi R\frac{\Delta b_1}{B} \tag{5}$$

This is the simplified solution for brute-force extraction (BE) which the particle is extracted before crossing the resonance. In fact, Eqs. (3) and (5) differed only by $\frac{1}{\nu_r^2-1}$ due to the adiabatic increment of oscillation in precessional motion after passing through the resonance. For instance, taking B=2.45 T at an extraction radius of 40 cm, 1.7 mT and 17 mT is required to generate a separation of 5 mm by PE. However, 17 mT is needed to generate a separation of 5 mm by BE

Initialization

Orbit analysis of these two different mechanisms were performed in SNOP [2]. A centered accelerated equilibrium orbit is first obtained by optimizing the initial conditions of single particle trajectory with a starting energy of 50 MeV without any harmonic bump. Then, 2 harmonic coils are added and optimized further to obtain a sufficient final-turn separation. The top-view harmonic coils with its corresponding harmonic component is shown in Fig. 2. Some of the initial conditions used are shown in Table 1.

Table 1: Initial Conditions of PE and BE in SNOP

	PE	BE
Energy (MeV)	1.04	
Azi. angle	0°	
Radius (mm)	59.9773	59.4241
p_r (mrad)	24.6	0.873
rf phase	87.4983°	92.7853°
No. of HC	2 (Opposite current)	
HC diameter (cm)	10	8
HC radial/azi. position	$39/25^{\circ}$	$35/-25^{\circ}$
Max B_1 (mT)	~ 1.45	~ 5.2
ESD arc span	80º	
$\overrightarrow{E_{ESD}}$ (kV/cm)	140	175
No. of turn until extraction	168	157

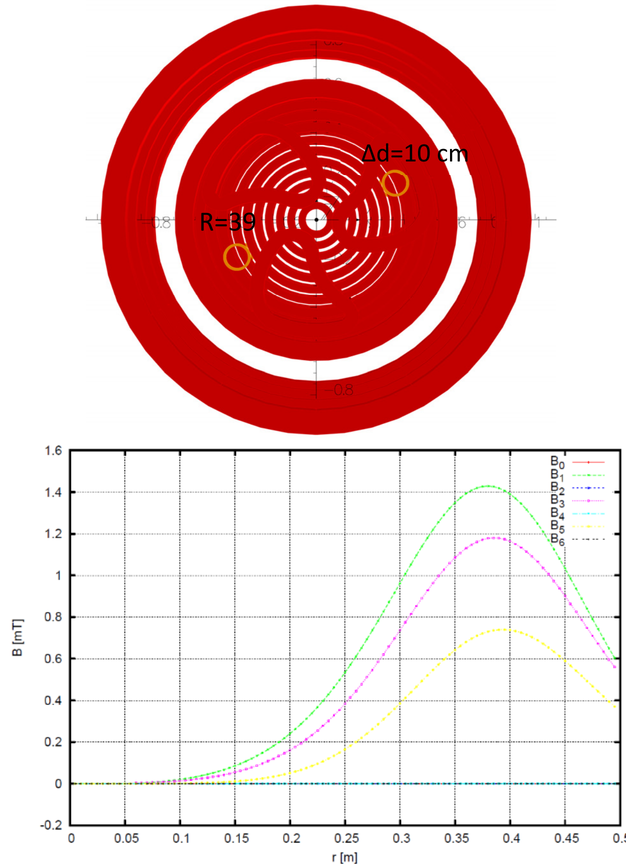

Figure 2: (top) The top-view of the harmonic coils used in PE and (bottom) its corresponding harmonic component of magnetic field.

RESULTS AND DISCUSSIONS

Single particle tracking

PE A reference particle was simulated in SNOP using initial condition given by Table 1. The last three turns of the particle is shown in Fig. 3(a). With the optimized harmonic bump, the final-turn occurs at turn 168th with a final energy of 53.4 MeV. The ΔR between the final turn and the penultimate turn is about 3 mm using an electrostatic field of 140 kV/cm spanning through 80º at 320º.

BE Similar to PE, single particle tracking was performed for BE using conditions in Table 1. The last three turns of the particle is shown in Fig. 3(b). As extraction occurs before the resonance, the extraction energy is 49.9 MeV at turn 157th, which is 11 turns earlier than PE. The ΔR between the final turn and the penultimate turn is about 3 mm. As extraction occurs at an inner radius, a higher electrostatic field of 175 kV/cm is used spanning through an angle of 80º at 320º.

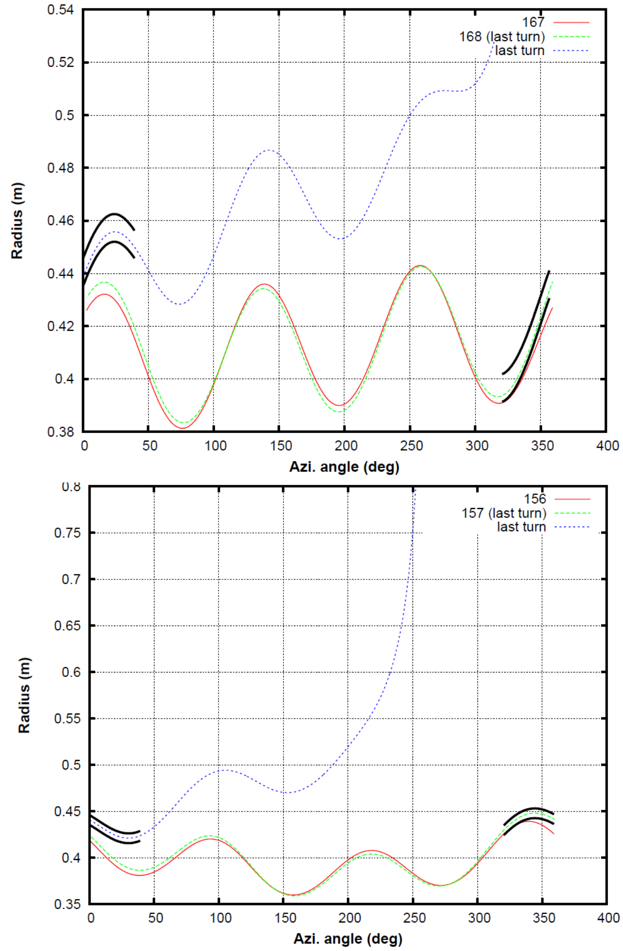

Figure 3: Final few turns of single particle tracking by (a) *top:* PE and (b) *bottom:* BE.

Multi-particle tracking

10k macro particles were simulated using similar initial conditions as given in Table 1 for multi-particle tracking. A matched beam of transverse rms emittance of 2π mm mrad was injected for a 1 μA and 1 mA beam respectively. The beam was assumed to be monoenergetic without any longitudinal spread (σ_E= 2 %, σ_{rf}=2°). The ESD septum was taken to be 0.5 mm for better heat deposition. The radial position of ESD was optimized to allow the most number of particles passing through the ESD column.

PE Figure 4 shows the R-z plot and the radial phase plot at the entrance plane and exit plane of ESD of a 1 μA beam. Despite of a non-linear distortion and growth in the emittance due to the resonance-crossing, the beam separation appears to be performing better than the turn-separation of a single particle. The final-turn separation between the peaks of the penultimate turn (167th) and the last turn (168th) is very distinct (about 4 mm). This is sufficient to cleanly separate and extract a beam with radial size of 1 mm. Thus, single-turn extraction is possible with a promising beam quality. The extracted beam has a good confined transverse rms emittance of 3.25π mm mrad and 0.75π mm mrad in r and z respectively at the exit plane of ESD.

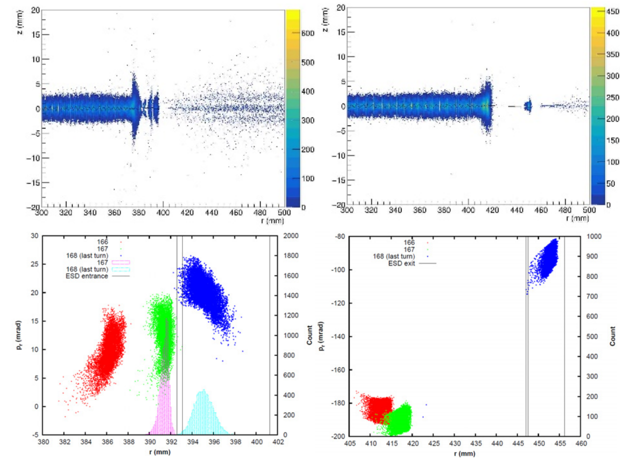

Figure 4: R-z plot and radial phase diagram of the final few turns of a 1 μA beam for PE. The bunch from final-turn (blue) is well separated from the penultimate turn (green). The results are taken at plane of ESD (a) *left:* entrance (320°) (b) *right:* exit (40°).

BE Figure 5 shows the R-z plot and the radial phase plot at the entrance plane (320°) and exit plane (40°) of ESD of a 1 μA beam. From Fig. 5, blow-up in z direction is less severe in BE as extraction occurs right at the verge of resonance crossing. Although the peak-to-peak separation between the final and penultimate turn of ~3.5 mm is close to the one of PE, almost 40 % of the beams are overlapped. Absolute separation between consecutive bunches without having severe beam distortion is almost impossible for HTS-SC as the harmonic bump generated by an air-core superconducting coil does not have a sharp-edge. As a result, multi-turn extraction is required and we expect a greater energy spread as compared to PE. The average rms emittance as a result of multi-turn extraction 2.18π mm mrad and 0.77π mm mrad respectively in r and z direction. The survival rate and the extraction efficiency of PE and BE are shown in Table 2.

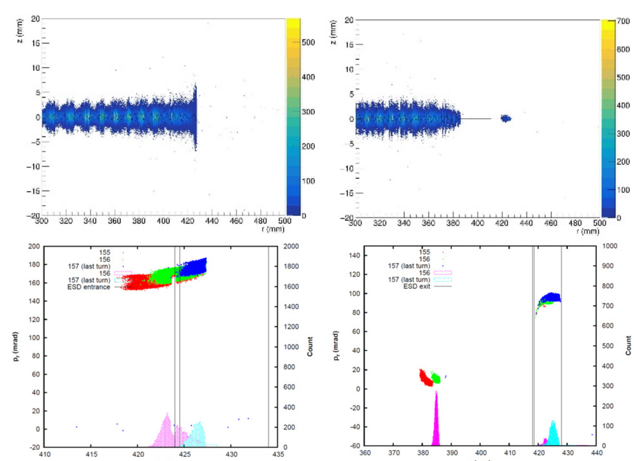

Figure 5: R-z plot and radial phase diagram of the final few turns of a 1 μA beam for BE. The results are taken at plane of ESD (a) *left:* entrance (320°) (b) *right:* exit (40°).

Table 2: Summary of the Performance of PE and BE

Parameters	**PE**		**BE**	
	1 μA	1 mA	1 μA	1 mA
Survival at ent. (%)	99.48	80.40	84.2	81.88
Survival at exit (%)	95.87	56.76	42.07	29.74
Ext. efficiency (%) $\frac{survival\ at\ ESD\ exit}{survival\ at\ ESD\ ent.}$	96.37	70.6	50	36.32
Turns of extraction	1	5	4	9

CONCLUSION

In conclusion, PE is a better extraction mechanism for HTS-SC due to its satisfactory performance as a whole. The extraction efficiency of PE is higher for both 1 μA and 1 mA beams. Despite of the risk of emittance blow-up passing through $\upsilon_r = 1$ resonance, the amplitude can be controlled with an optimized B_1 bump. A relatively smaller B_1 bump as well as ESD field of 1.45 mT and 140 kV/cm is required in PE. Distinct beam separation is achieved using PE. Thus, single-turn extraction is possible using PE to extract beam to extract beam with a confined beam size.

REFERENCES

[1] H. W. Koay, M. Fukuda, H. Kanda and T. Yorita, "Beam dynamic study of a compact superconducting skeleton cyclotron (SSC) for BNCT and radioisotope production," in *Proceedings of the 16th Annual Meeting of Particle Accelerator Society of Japan*, Kyoto, Japan, 2019.

[2] V. L. Smirnov and S. B. Vorozhtsov, "SNOP—beam dynamics analysis code for compact cyclotrons," in *Proceeding of XXI Russian Accelerator Conference*, 2012.