SLOW BEAM EXTRACTION FROM TARN II

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Abstract

A slow beam extraction system for TARN II is under construction to provide heavy-ion beams (p, α ~ Ne) at intermediate energy (150~ 350 MeV/u). The third order resonance extraction with tuning of lattice quadrupole magnets is to be used. The emittance of the extracted beam and the extraction efficiency are estimated to be 5π mm·mrad and more than 89%, respectively.

Introduction

At Institute for Nuclear Study, University of Tokyo, a synchrotron/cooler ring, TARN II, has been under construction since 1984. TARN II aims at acceleration of heavy ions up to Ne into the intermediate energy region (150~ 350 MeV/u) and capability to reduce the emittance and momentum spread of the ion beam with an electron beam cooling.[1] In order to respond to the demands for heavy ions with intermediate energy to utilize for fundamental research of biomedical irradiation, a slow beam extraction system has been designed and its hardware equipments have been already under construction.[2,3]

In the present paper, the scheme of the slow beam extraction adopted at TARN II is described at first. Then the results of beam tracking simulation based on this system are presented. Finally, the expected quality of the extracted beam is given.

Slow Beam Extraction System

The layout of the slow beam extraction system is shown in Fig. 1 together with the arrangement of the main magnets of TARN II. The essential parameters of this extraction system are listed up in Table 1.

The operating point of TARN II at the injection stage is chosen to be around (1.75, 1.80). If the half-integer resonance (ν_H=3/2) is to be used, it needs crossing of the third order resonance (ν_H=5/3), which requires additional care for compensating the third order stopband. Mainly from this reason, the third order resonant beam extraction is adopted here.

The extraction process is performed in the following procedure.

a) Nearly at the end of beam acceleration stage, such an orbit bump as makes aperture minimum at the entrance of an electrostatic septum (ES) is made by exciting bump coils 1, 2 and 3, which are wound at backlegs of main dipole magnets.

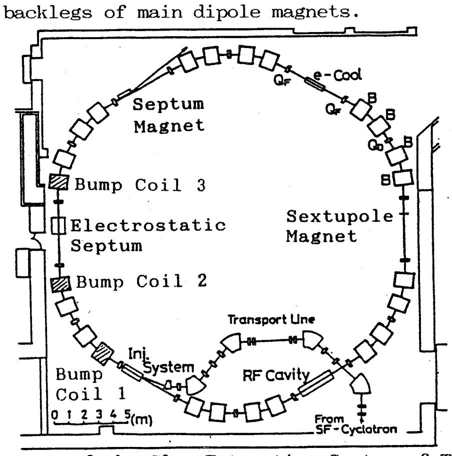


Fig. 1 Layout of the Slow Extraction System of TARN II.

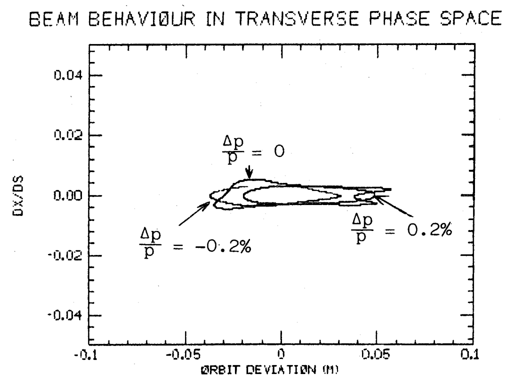


Fig. 2 Behaviour of the injection beam with emmitance of 150π mm·mrad in transverse phase space with full excitation of the resonance exciter.

b) The operating point is moved from (1.75, 1.80) to (1.6667, 1.80) by changing the excitation currents of the quadrupole magnets in the lattice after the completion of process a). Precise tune change is made by exciting additional coils attached to the main quadrupole magnets after reaching close enough to the resonance (ν_H=5/3).

c) Beams which have deviated to the distance more than 75 mm outside from the central orbit at the entrance of the ES are deflected outward as large as 5.8 mrad by the static high voltage of the ES.

d) A septum magnet (SM), which is located almost one cell downstream from the ES to accept all the deflected beams in procedure c), gives much larger deflection angle (85 mrad) to guide the beam outside the ring.

A sextupole magnet for excitation of the third order resonance, ν_H=5/3, is located at the position indicated in Fig. 1. Throughout the whole process from injection to extraction, it is energized at the level corresponding to the extraction beam energy. The effect of existence of such a rather strong sextupole field during injection and acceleration stage is investigated by beam tracking with a computer. Typical result is shown in Fig. 2. It is seen that although the effect of nonlinear magnetic field is observed, the beam motion is still bounded and stable acceleration can be expected with existence of such a sextupole field. In this situation, rather large chromaticities in both horizontal and vertical directions are anticipated, however tune spread of the beam with fractional momentum spread of $\pm 0.2\%$ remains well inside the triangular region surrounded with nearby resonances as shown in Fig. 3. So we have decided to use the sextupole magnet with DC characteristics[4] as a resonance exciter.

Table 1

Parameters of Slow Extraction System of TARN II

Ion Species	p, α ~ Ne
Beam Energy	150 ~ 350 MeV/u
Extraction Scheme	Third Order Resonance Extraction
Operating Point	(1.6667, 1.80)
Septum Position	75 mm outside from centeral orbit
Beam Emittance	Circulating Beam $\leqq 50\pi$ mm·mrad
	Extracted Beam ~ 5π mm·mrad
Momentum Spread	$\pm 0.2\%$

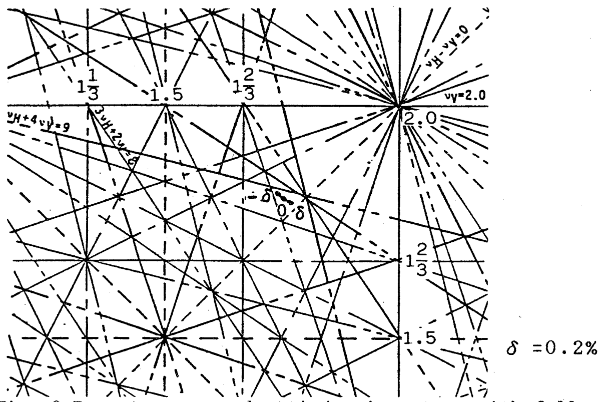


Fig. 3 Beam tune spread at injection stage with full excitation of the resonance exciter.

Hardware equipments for the extraction system described above are listed up in Table 2 with their main specifications.

Beam Tracking during the Extraction Process

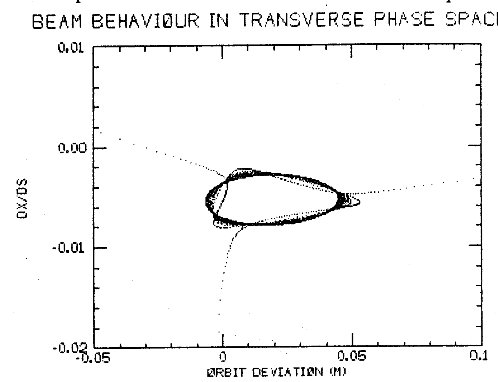
At TARN II, the horizontal aperture is basically designed to be ± 100 mm, but it is limited at much smaller value as ± 70 mm at several places where electrostatic pick-ups are installed. It is enevitable to investigate the beam trajectory just before extraction over the whole circumference and make it sure it can safely circulate in the ring until it enters into the aperture of the ES. For this purpose, beam tracking is performed. Beam motion in transverse phase spaces is traced with use of transfer-matrix formalism. The nonlinear element is treated with thin lens approximation. The beam momentum is kept at the certain value because during the extraction process no RF voltage is to be applied to make flat time structure of the extracted beam. The horizontal tune of the ring is gradually shifted from 1.75 to 1.6667 by changing the excitation levels of quadrupole magnets linearly. In Fig. 4, typical example is given for such a beam with central momentum and emittance of 50π mm · mrad. As the result of the procedure (a) in the previous section, the deviation of the bump orbit from the central orbit and its derivative at the entrance of the ES as large as 22 mm and -5.2 mrad are taken into account. The behaviour of the beam in the horizontal transverse phase space at the entrance of the ES is shown in Fig. 4(a) through the whole process from just after acceleration to the end of extraction. In order to clarify this situation, the beam behaviour is displayed separately according to the horizontal tune in Fig. 4 (b) and (c). The beam's motion is almost not affected by the nonlinear field of the resonance exciter and the beam circulates on a ellipse as shown in Fig. 4(b) while ν_H remains higher than 1.68. Then the motion begins to be distorted and the ellipse is distorted to triangular shape little by little after the distance from the resonance in the tune diagram approaches closer than 0.008. Finally after the tune difference comes to 0.0033, the beam begins to move on the separatrix shown in Fig. 4(c) and its amplitude blows up. For the purpose of checking the validity of such tracking, an analytical calculation of the unstable fixed points and the separatrix is performed[5] assuming the beam emittance of 50π mm · mrad and the same orbit bump as the tracking. The solid lines in Fig. 4(c) show the ones obtained by such a calculation, which coincide well in global feature with the tracking result.

When the deviation of the beam from the central orbit at the entrance of the ES exceeds the septum position of the ES(75 mm in the present case), the results are traced back to three turns before and the beam positions at the whole circumference in these turns are calculated. In Fig. 5, a typical example of such calculation is shown. From the figure, it is seen that the largest deviation of the beam position at other places than the ES occurs at the position of

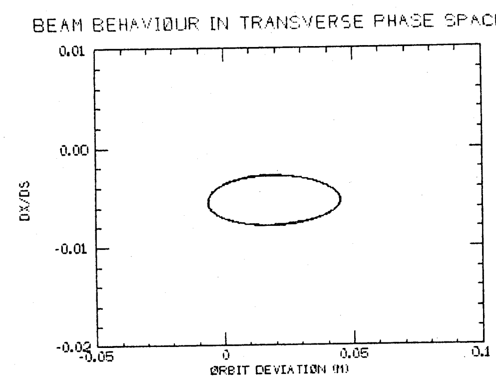
Table 2

Hardware Equipments for Slow Beam Extraction

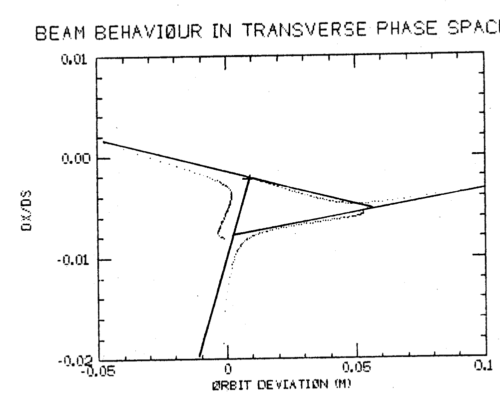
Sextupole Magnet	B"L/Bρ = 0.3015 1/m² (DC mode)
Electrostatic Septum	E = 70～85 kV/cm, L = 1.0 m, Deflection Angle = 5.8 mrad, Septum Thickness = 0.15 mm
Septum Magnet	B = 5 kG, L = 1.0 m, Deflection Angle = 85.2 mrad, Septum Thickness = 9 mm
Bump Coil 1	Deflection Angle = 5.4 mrad
〃 2	〃 =-7.1 mrad
〃 3	〃 = 7.1 mrad



(a) throughout the whole process



(b) ν_H = 1.75 ～ 1.68



(c) ν_H = 1.670

Fig. 4 Beam behaviour in the horizontal transverse phase space at the entrance of the ES.

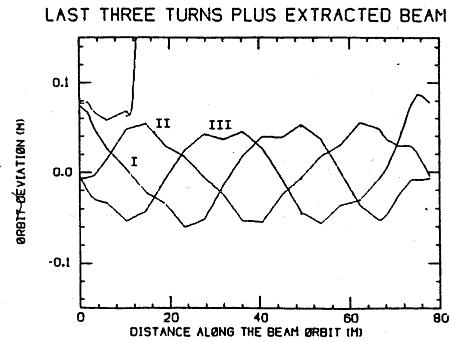


Fig. 5 Beam positions in the horizontal direction during last three turns just before extraction and after deflection by extraction septums.

Q_F magnet just before the ES and its size is assured to remain inside of the vacuum chamber in the Q_F magnet ($\pm$ 95 mm). The beam positions in such three turns are studied for all the beams with fractional momentum spread of $\pm$ 0.2% and emittance from 5π (simulates beam with very small amplitude) to 50π mm$\cdot$ mrad and are checked to be well inside of the aperture of the various equipments distributed around the ring including the electrostatic pick-ups with the minimum aperture.

Characteristics of the Extracted Beam

The turn separation (the amplitude growth of beam in three turns) just before entering into the aperture of the ES can be studied at the same time with the beam tracking described in the previous section. The results are summarized in Table 3 for various beam conditions. The turn separation of the beam is calculated analytically with the treatment given by D. A. Edwards[6]. The calculated result for the beam with emittance of 50π mm$\cdot$ mrad and central momentum is 3 mm, which seems to be in good agreement with the above result. The septum wire of the ES is 0.09 mm in diameter, however its effective thickness is estimated to be 0.15 mm considering the deformation and misalignment of the wire. The extraction efficiency given in Table 3 is calculated assuming this value.

In order to estimate the emittance of the extracted beam, beam location in the horizontal transverse phase space at the exit of the SM is calculated as shown in Fig. 6. In the calculation, the ap

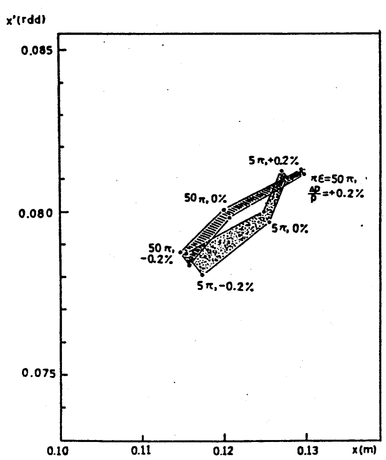


Fig. 6 The shape of the extracted beam in the horizontal phase space at the exit of the SM. Values of $\pi\varepsilon$ and Δ p/p in the figure represent ones while circulating in the ring.

Table 3

Turn Separation and Extraction Efficiency

Condition of Circulating Beam Emittance (mm$\cdot$ mrad)	Δ p/p (%)	Turn Separation(mm)	Extraction Efficiency(%)
5π	0.2	2.5	94
5π	0.0	4.0	96
5π	-0.2	6.3	98
50π	0.2	1.4	89
50π	0.0	2.6	94
50π	-0.2	4.2	96

plied electric field on the ES is changed from 85 kV/cm to 70 kV/cm from the beginning to the end of the extraction process to compensate the angle difference of the extracted beam at the entrance of ES depending on the oscillation amplitude of the beam before extraction. During the slow extraction, the beam with the largest emittance of 50π mm$\cdot$ mrad begins to be extracted at first and then gradually beams of the smaller eminttance are extracted according to the approach of the horizontal tune to the resonance and finally very small emittance (here we use 5π mm$\cdot$ mrad instead of 0 from computational reason) beam near the equilibrium orbit is extracted. The instantaneous beam emittance is estimated $\sim 2\pi$ mm$\cdot$ mrad. However, it varies depending on time. Time integrated emittance of the extracted beam is estimated $\sim 5\pi$ mm$\cdot$ mrad. In Fig. 7, the beam trajectory of the extracted beam is shown for the straight section where the SM is located. It is seen that all the beams deflected by the ES located upstream are guided into the aperture of the SM clearing its septum thickness of 9 mm.

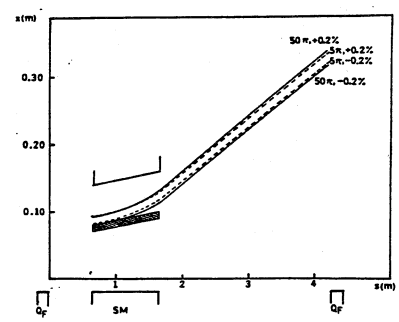


Fig. 7 Orbits of the extracted beam at the straight section where the SM is located.

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