DESIGN OF THE SLOW EXTRACTION SYSTEM AT THE TARN II

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ABSTRACT

The slow extraction system at the TARN II is designed. The beam dynamics related to the extraction is calculated with use of the second order particle tracking program. The circulating beam with emittance (up to 120π mm·mrad) with the fractional momentum spread of $\pm 0.2\%$ can be extracted with high efficiency ($\sim 98\%$) and with its small emittance (less than 1π mm·mrad).

INTRODUCTION

The resonance extraction methods have long been applied in many synchrotrons. Efforts are aimed at getting a high efficiency of extraction and good quality of the extracted beam. The TARN II has the lattice with sixfold symmetry, and its horizontal tune value Q is 1.75 for operation of acceleration and 1.75 or 2.25 for that of electron cooling.[1]

In the present paper, we describe the refinement of design for the TARN II [2], in which the slow beam extraction is considered by using the third integer resonance ($Q_{res}=5/3$). Together with the excitation of resonance induced by the sextupole magnets, the method of the cooperative tracking is utilized at the time of extraction between the main dipole magnets for the displacement of orbit and quadrupole magnets for the tune shift, which establishes the excellent extraction in consequence of the chromaticity adjustment.

SEPARATRICES IN THE THIRD INTEGER RESONANCE

In order to have a good efficiency of the extraction, the alignment of the outgoing separatrices at the extraction point in the ring, (usually at the electrostatic septum) is the matter of great importance. Using the notation in the complex plane $Z_A=(X,iX')$, where X and X' are the normalized units for position and inclination of each particle, the alignment condition can be written as $y'=\mathrm{Im}[Z_A\cdot\exp(-i\phi_e)]$ remaining constant whatever are the amplitude of oscillation, the position of the particles or the momentum displacement from its central value. Here y' is the projection on an axis perpendicular to the separatrix. The ϕ_e is the inclination of the separatrix[3].

The contribution to Z_A are betatron oscillation; $Z\beta=(2a/\sqrt{3}\cdot\exp\{i(\phi_e-\pi/6\cdot\mathrm{sign}(\Delta Q)\}$, dispersion function ; $(D+iD')\cdot(\Delta P/P-\Delta B/B)$ and effect of local bump orbit Z_{bu} (taking it to be zero for the moment) The ΔQ is the tune shift from the resonance value. The value of a is the amplitude of each particle which is derived from the enclosed emittance $\pi\beta_e\varepsilon=\sqrt{3}\cdot a^2$. ($\beta_e$; beta function at the extraction point)
Then y' becomes

$$y'=\{-a\cdot\mathrm{sign}(\Delta Q)/\sqrt{3}+D\cdot\cos(\phi_e+\tau)\cdot(\Delta P/P-\Delta B/B)\} \quad \cdots(1)$$

where $D=(D^2+D'^2)^{1/2}$, $\tan\tau=D/D'$.

We devide the chromaticity of the machine into two components ; ξ_Q and ξ_B. The ξ_Q is the part of the chromaticity coming from the focusing force and the ξ_B is the part coming from orbital effect: ξ_Q is a constant for a given lattice structure, while ξ_B can be changed linearly by adding sextupole magnets. In first order the variation of tune can be written for deviation of momentum and change of the bending field as follows;

$$\Delta Q/Q=\xi_B\cdot(\Delta P/P-\Delta B/B)+\xi_Q\cdot\Delta P/P \quad \cdots(2)$$

For the resonance condition of the particles at the limit of stability, one has

$$\Delta Q_0-\Delta Q_a+Q\cdot\xi_B\cdot(\Delta P/P-\Delta B/B)+Q\cdot\xi_Q\cdot\Delta P/P+\delta Q=0 \quad \cdots(3)$$

where ΔQ_0 is the difference between the tune of the machine during accerelation and the shifted tune of the beam just before the excitation of resonance, where a reference particle is generally taken at the center of the momentum distribution. The $(-\Delta Q_a)$ represents the tune shift of a particle having an amplitude of oscillation a; $\Delta Q_a=(S/4\pi)\cdot(a/\sqrt{3})\cdot\mathrm{sign}(\Delta Q)$, in other words, ΔQ_a shows the tune shift dependence on particles of different amplitude in the phase space. The δQ is the tune shift made by the change of the strengths of quadrupole magnets during the extraction. However, by the change of the tune alone it is not possible to align separatrices of all the particles in the circulating beam.

From the above equations, it leads to the following equation;

$$y'=\{a\cdot\mathrm{sign}(\Delta Q)/\sqrt{3}\}\cdot[-1+\{S/(4\pi Q\xi)\}\cdot D\cdot\cos(\phi_e+\tau)] \\ -\{\Delta Q_0+\delta Q+Q\cdot\xi_Q\cdot(\Delta B/B)\}\cdot D\cdot\cos(\phi_e+\tau)/(Q\cdot\xi) \quad \cdots(4)$$

where $\xi=\xi_Q+\xi_B$.

Then to maintain y' constant, two conditions are needed;

$$4\pi Q\xi/S=D\cdot\cos(\phi_e+\tau) \text{ and } \delta Q=-Q\cdot\xi_Q\cdot\Delta B/B \quad \cdots(5)$$

The first condition is the relation which should be satisfied by following parameters, ξ (chromaticity), S (amplitude of sextupole for the resonance) and other machine parameters.

In the study of simulation, we use the second order tracking program of particles "DIMEX" and the associated program made for the extraction utilizing the third integer resonance.[4] The formula given above are therein modified to the form of including second order terms ; those of the momentum fraction, change of bending field and chromaticities.

The solution of the separatrix at the electrostatic septum is shown in Table 1. In the TARN II, natural horizontal chromaticity in first order is supposed to be $\xi_Q{}^N=-0.6$ and $\xi_B{}^N=+0.3$, therefore, it is

Table 1 Obtained parameters in the simulation

Tune value for extraction	:	$Q_H=1.675$ $Q_V=1.250$
Amplitude of sextupole	:	$S=7.5$ (m^{-3})
Phase of sextupole	:	$\phi_s=15.0$ (deg.)
Strengths of sextupoles	:	$S_f=-2.06$ $S_d=0.305$ (m^{-3})
		$S_{x1}=4.19$ $S_{x2}=0.753$
Shift of chromaticities	:	$\Delta\xi^H=-0.3$ $\Delta\xi^V=0.0$
Emittance of the beam	:	$\varepsilon^H=66\pi$ $\varepsilon^V=10\pi$ (mm·mrad)
Momentum spread	:	$\Delta P/P=\pm 0.2$ %
Pre-displacement of orbit	:	DBSB = 0.4 %
Variation of bending magnets	:	-0.39 % for $\Delta P/P=-0.2$ %
		-0.21 % = 0.0 %
		-0.01 % = 0.2 %
Variation of quadrupole magnets	:	-0.77 % for $\Delta P/P=-0.2$ %
		-0.58 % = 0.0 %
		-0.39 % = 0.2 %
Position of the electrostatic septum	:	60 mm

chosen that the addition of sextupoles causes the shift of chromaticity $\Delta \xi_B=-0.3$ so that the effect of the ripple coming from the main bending magnets becomes as small as possible. The strengths of sextupoles should be enough for gaining the turn separation of the extracted beam within the fabrication limit. The combination of the positions and strengths of the sextupole magnets sets the phase of the extraction. The inclination of the particles at the extraction point is determined by consideration of the transport of the beam after the extraction point and of the associated bump orbit. In order to obtain the sufficient turn separation, the circulating beam is displaced toward inside by strengthening the bending field (this value is denoted by DBSB) after reach of the tune value at 1.675. Afterwards, the process of induction of resonance starts by exciting the sextupoles and the decreasing the fields of bending and quadrupole magnets. The obtained separatrices are shown in Fig. 1.

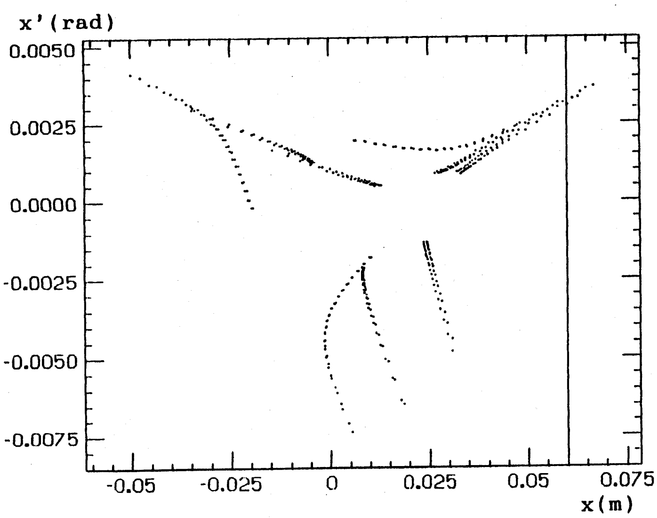

Fig. 1 Separatrices of the beam for the combination of $\Delta P/P=\pm 0.2$ % and emittances of 0π, 16π and 66π mm·mrad in the horizontal phase space.

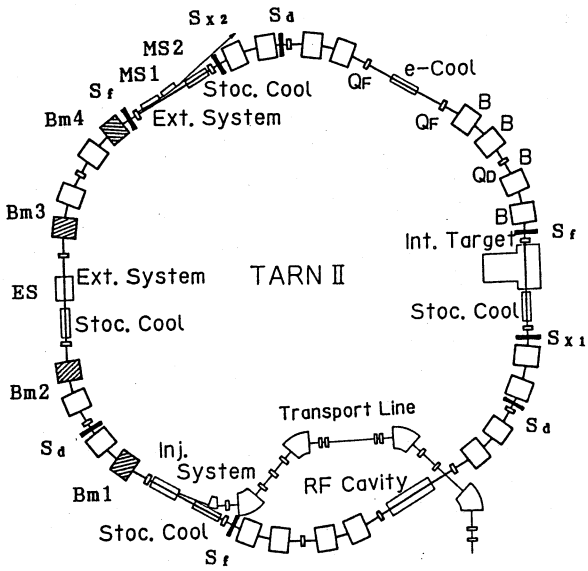

Fig. 2 TARN II with the extraction system ; S_f and S_d are sextupole magnets for chromaticity adjustment. S_{x1} and S_{x2} are for resonance excitation. ES is an electrostatic septum. MS1 and MS2 are magnetic septa. Bm1～4 are bump magnets.

Extraction system of the ring

Study in the beam dynamics of the extraction described above is performed under the following configurations in the TARN II. We place the extraction elements shown as in Fig. 2. These are ;

i) Six sextupole magnets placed neighboring to the horizontal or vertical focusing quadrupoles for the chromaticity adjustment and two sextupole magnets as the resonance exciters.

ii) Four bending magnets which are used as bump magnets for distorting the local closed orbit owing to the attached back leg coil.

iii) An electrostatic septum and two magnetic septa as extracters.

iv) Main dipole and quadrupole magnets for shift of closed orbit and tune toward the resonance.

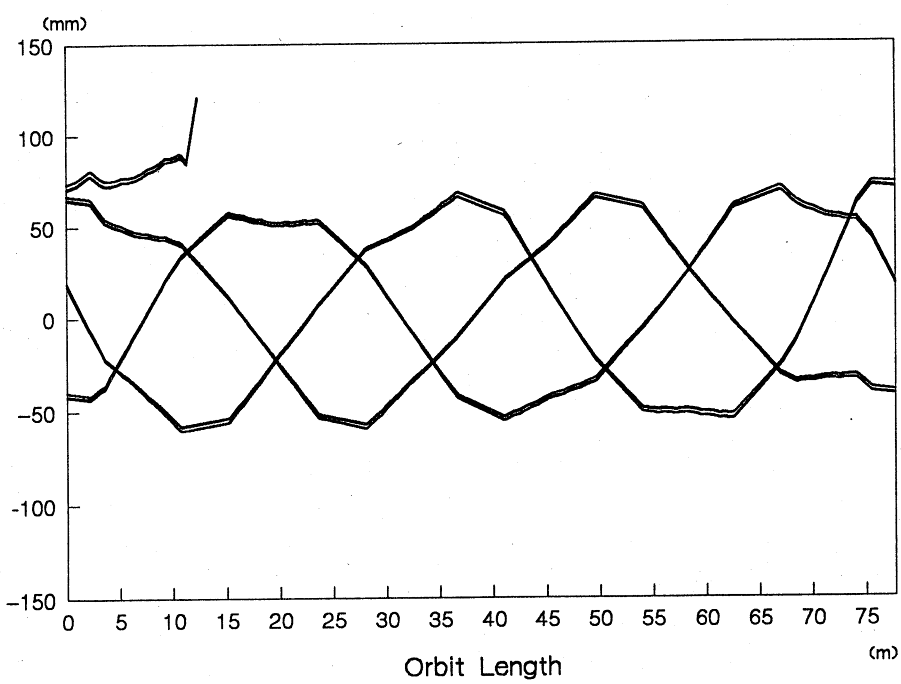

Fig. 3
Beam trajectory of the extracted particles for last three turns.
Horizontal axis is along the whole circumference of the ring. The starting point of the left side corresponds to the position of the ES.
The upper portion of the trajectory shows the extracted beam.

The position of each element is determined by the consideration of the beam dynamics as well as the environmental conditions of different functions in the ring. Position of the ES is set with the distance of 70 mm from the central orbit of the ring. Local bump orbit is produced with the displacement of Δx_e=10 mm and its inclination of $\Delta x_e'$=-3.4 mrad at the extraction point. These values are chosen so that all the particles are going parallel into the electrostatic septum which is set parallel to the beam line. Therefore, the distance from the closed orbit to the ES is 60 mm. The beam trajectories in the ring of extracted particles for last three turns are shown in Fig. 3, which lie within the geometrical limit along the circumference of the ring.

BEAM ENVELOPE IN EXTRACTION LINE

As shown in Fig. 2, the entrance of the ES is set at middle of the straight section, and two magnetic septa are placed in the next straight section. Once after the particles are led to the inside gap of the ES, they can be separated from the circulating one and should be passed through these magnetic septa.
The parameters of the septa are listed in the Table 2. The amounts of kicks are corresponding to the accelerated ions with charge to mass ratio of 1/2 and its energy of 350 MeV/u. The kick of the ES is small amount. If there is not any kick between the ES and the MS, the extracted beam envelope approaches toward the center of circulating beam in the next straight section due to the phase advance. However, the forementioned bump orbit solves this problem because the negative value of $\Delta x_e'$ forces the 3rd bump magnet to have the kick outward by proper amount. By use of the program[5], the beam envelope of the extracted beam from the ES to the entrance of the MS2 is shown in Fig. 4. For the beam of the different momentum fraction, nearly the same envelopes are drawn, due to the fact that the tracking of the variation of main dipole and quadrupole magnets have the different values in favor of the similar trajectories.

Table 2 Parameters of the extracters and kicks of the bump magnets

Type	Thickness (mm)	Field (KV/cm),(KG)	Length (m)	Kick (mrad)
ES	0.09	60	1.0	4.96
MS1	9	5	1.0	85.3
MS2	35	15	0.7	182

Bm-1 :	1.88 mrad	Bm-2 :	-4.51 mrad
Bm-3 :	4.51 mrad	Bm-4 :	-1.88 mrad

EXPECTED PROPERTIES OF THE EXTRACTED BEAM

In the TARN II which is connected with the SF cyclotron, the common energy of the injection is 20 MeV/u with maximum emittance of 300π mm·mrad due to the multiturn injection. Accordingly, the emittance at 350 MeV/u becomes 66π mm·mrad. Study of the extraction shows that the lowest beam energy which can be extracted without loss at the different points from the extraction point turns out to be 120 MeV/u, which has the emittance of about 120π mm·mrad. The largest envelope of circulating beam along the ring where the beam energy is that of injection is shown in Fig. 4.

The important quantities in the system is its efficiency of extraction, which is closely related to the turn separation, and the spread of the inclination of the beam at the extraction point.
The values of turn separations in the simulation are listed in Table 3. The inclinations of all the particles in the separatrices are 3.40 ± 0.35 mrad.

Consequently, the rough estimate of the extraction efficiency is 97.8%, and the extracted beam emittance becomes 0.69π mm·mrad. In case of the lowest energy of 120 MeV/u, almost the same efficiency is obtained. The extracted beam emittance shows a little bit of increase, but still the value of 0.75π mm·mrad.

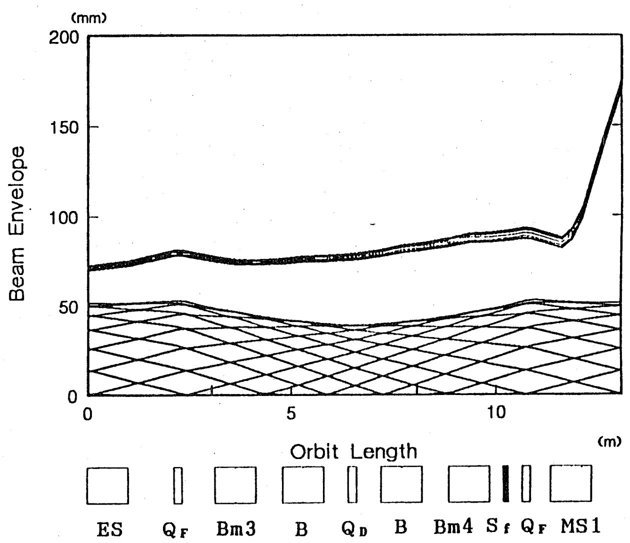

Fig. 4 Beam envelope of the extracted particle from the entrance of the electrostatic septum ES to that of the magnetic septum MS2 and circulating beam envelope at the injection energy where the emittance of beam is 300π mm·mrad.

Table 3 Turn separations calculated at 350 MeV/u

Position of the particle (in terms of emittance)	ΔP/P +0.2 %	-0.2 %
0π mm·mrad	4.5 mm	5.1 mm
16π mm·mrad	7.6 mm	7.1 mm
66π mm·mrad	6.2 mm	7.0 mm

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REFERENCES

1) A. Noda et al., IEEE Trans.,NS-32,No.5,p2684,1985

2) M. Takanaka et al., *ibd*,p2436,1985

3) W. Hardt, PA/DL/LEAR 81-6,1981

4) CERN,Division of LEAR,Private communication

5) K. Noda, INS Report to be published.