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INJECTION AND EXTRACTION SYSTEM OF THE RCNP RING CYCLOTRON

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ABSTRACT

The system of the injection and extraction of the RCNP Ring Cyclotron is briefly summarized. Some design principles and the present stage of the design are also briefly described.

INJECTION

The accelerated beam from the AVF cyclotron will be transported by the beam line "C-course" through the "North Experimenal Room" to the Ring Cyclotron. The beam will already be well shaped and momentum-selected at the exit of the "Room", and then will enter the injection line of the Ring Cyclotron after about 20 m drift space. The beam optics from the AVF cyclotron to the entrance of this beam line (point A in Fig. 1) will be so conviniently adjusted without any difficulty that many modes of operation, for example, very high resolution/high quality mode, high intensity mode and very short pulse mode, etc., are easily available. Therefore the injection line operates as a matching section to the Ring Cyclotron. The elements are four bending magnets (BI1~4), eight quadrupole magnets (QI1U, QI1D,····, QI4D), two magnetic channels (MIC1, 2), two electrostatic channels (EIC1, 2), an additinal quadrupole, and two pairs of steering dipole magnets(ST1 ~ST4). These are schematically shown in Fig. 1. The transversal emittances of the beam from the AVF cyclotron are supposed to be ~10π mm-mrad for the both planes, then the beam shapes in phase space will be ~3 mm×~3 mrad at the point A, which is an image point of the final doubly focussing and doubly achromatic point of the transport line from the AVF cyclotron. The optics from A to the entrance of MIC1 is shown in Fig. 2. The beam envelope (half size) is almost less than 10 mm. The matching of the dispersion and the eigen ellipses in phase space is adjusted by the quadrupoles and the perturbed injection orbit in the valley region of the Ring Cyclotron (between QI4D and BI2) is corrected by the steering dipole magnets. Table 1 summarizes the present design values of the main parameters of the injection elements.

EXTRACTION

The extraction system consists of two electrostatic channels (EEC1, 2), two magnetic channels (MEC1, 2), two bending magnets (BE1, 2) and several quadrupole magnets (QEn's). These are also schematically shown in Fig. 1. The extracted beam is transferred at the point B to the beam transport lines for the experiments. The transversal emittance of the 400 MeV proton beam will be reduced to ~3π mm-mrad from ~10π mm-mrad by adiabatic damping. This just corresponds to the orbit separation of ~4 mm at the EEC1.

There will be at least two optics. The one is the tuning mode shown in Fig. 3 for the Ring Cyclotron, which is the transport line from the Ring Cyclotron to the beam dump through the doubly achromatic point B, where the beam envelope has the minimum or the eigen ellipses are almost as same as those at the exit of the Ring Cyclotron. The other is the extraction for experiments. For example, the optics to the "North Course" is shown in Fig. 4, where the parameters of the tuning mode should not be used because the vertical beam size becomes too large. The main reason of this problem is that the distance between the quadrupole magnets (QE3, QE4 and QE5) and the focal point B is too short. In these calculation, to obtain the waist (envelope minimum) is prior to focussing because the beam has a finite beam size at the exit of the Ring Cyclotron.

Table 1 also summarizes the present values of the main parameters of the extraction elements.

FIELD TOLERANCE OF MAGNETIC ELEMENT

The transversal emittance of the beam injected into the Ring Cyclotron would increase from the designed value by the phase space dilution due to the phase space mismatch. When the linear optics of the injection system is perfectly adjusted to the designed one, the main causes of the mismatch are unexpected kicks due to nonlinear magnetic fields in each injection element.

The emittance increase ($\pi\Delta\varepsilon$) can be described as $\Delta\varepsilon=\beta\theta^2$, where β and θ are the average of the beta function and a nonlinear kick (deflection) in a magnetic element. This increase should be less than $r\varepsilon_0$, where ε_0 is the designed emittance and r is the tolerable dilution factor, for instance, r=0.1.

For dipole magnets, θ is given by $\theta=\theta_B(\Delta B/B)$, where θ_B and $\Delta B/B$ are the bending angle and the maximum of the relative field error in the region of the beam size ($\pm\sqrt{\beta\varepsilon_0}$). From these, the condition for the field uniformity is obtained as,

$$\Delta B/B < (r\varepsilon_0/\beta)^{1/2}/\theta_B \text{ for } |x| < (\beta\varepsilon_0)^{1/2}.$$

If the dominant component of the field error is sextupolar, the equation becomes as,

$$|B''/B| < 2\{r/(\beta^3\varepsilon_0)\}^{1/2}/\theta_B.$$

For quadrupole magnets,

$$\theta = \ell\Delta B'(\beta\varepsilon_0)^{1/2}/(B\rho)$$
$$= K(\beta\varepsilon_0)^{1/2}(\Delta B'/B') < (r\varepsilon_0/\beta)^{1/2}$$
$$|\Delta B'/B'| < K^{-1}r^{1/2}/\beta,$$

where $K = B'\ell/(B\rho)$ (typically $K<2.0\ m^{-1}$).

Numerical examples for r=0.1 (10% increase) and $\pi\varepsilon_0$=10 π(mm-mrad) are as follows.

	Max. β(m)	
Dipole	5	$\lvert\Delta B/B\rvert<4.5\times10^{-4}/\theta_B$ for $\lvert x\rvert<7$ (mm)
		or $\lvert\Delta B''/B\rvert<18/\theta_B\ (m^{-2})$
Quadrupole ($K=2.0\ m^{-1}$)	20	$\lvert\Delta B'/B'\rvert<8\times10^{-3}$

DESIGN OF 1.8 T DIPOLE MAGNET

There are two 1.8 T dipole magnets, BI3 and BI4. The radius of cuverture is designed to be 0.75 m because of the tight spacing in the central region. The injection energy for the proton beam is ~65 MeV, which corresponds to ~15 kGauss, but for the α beam, the energy is about ~85 MeV and the magnetic field of these dipoles is ~18 kGauss.

The boundary conditions for BI4 are that this should be installed in atmosphere and the orbit separation is ~170 mm. The cross section is shown in Fig. 5. The coils of each pole consist from two pancakes. The one is flat and has 8-turn winding. The other is a saddle type and has 6-turn windings. Both are two channels of water cooling. The maximum excitation current and current density are 2000 A and 23 A/mm^2. The maximum temperature rise is estimated as 33°C under the pressure drop of 3 kg/cm^2.

The calculated field uniformity by TRIM is shown in Fig. 6. The sextupole component at 18 kG is ~8 (m^{-2}), which is about a half of the criterion given above (θB≃1 for BI4). To improve the field uniformity, using Permendur for the pole (hatched region in Fig. 5) is now considered.

For BI3, almost the same design guidance is approved except for the current density, and almost the same field quality is obtained.

Table 1
Main Parameters of the Injection and Extraction Elements

Element		BI1	BI2	BI3	BI4	MIC1	MIC2	QI	QM	EIC1,2	MEC1	MEC2	EEC1	EEC2	BE1	BE2	QE
Maximum field	(*)	15	15	18	18	3a)	0.5a)	10	1	100	1a)	10	100	100	16	16	20
Length	m	0.2	0.6	1.5	0.8	0.6	0.6	0.4	0.15	0.35	1	0.28	0.5	0.7	1.4	1.4	0.4
Radius of Curveture	m	0.9	0.9	0.75	0.75	0.8	0.8	-	-	-	1.8	-	-	-	2	2	-
Bending angle	deg.	9	40	111	60	~40	~40	-	-	-	30	8.5	-	-	40	40	-
Injection angle	deg.	0	0	20	8	-	-	-	-	-	-	-	-	-	0	0	-
Ejection angle	deg.	0	0	7	-13	-	-	-	-	-	-	-	-	-	0	0	-
Gap height	mm	40	40	33	33	33	33	-	-	10	33	33	10	10	40	40	-
Bore radius	mm	-	-	-	-	-	-	40	40	-	-	-	-	-	-	-	40

*) kG for bending elements, T/m for quadrupoles and kV/cm for electric channels.
a) variation from the field of the main magnet.

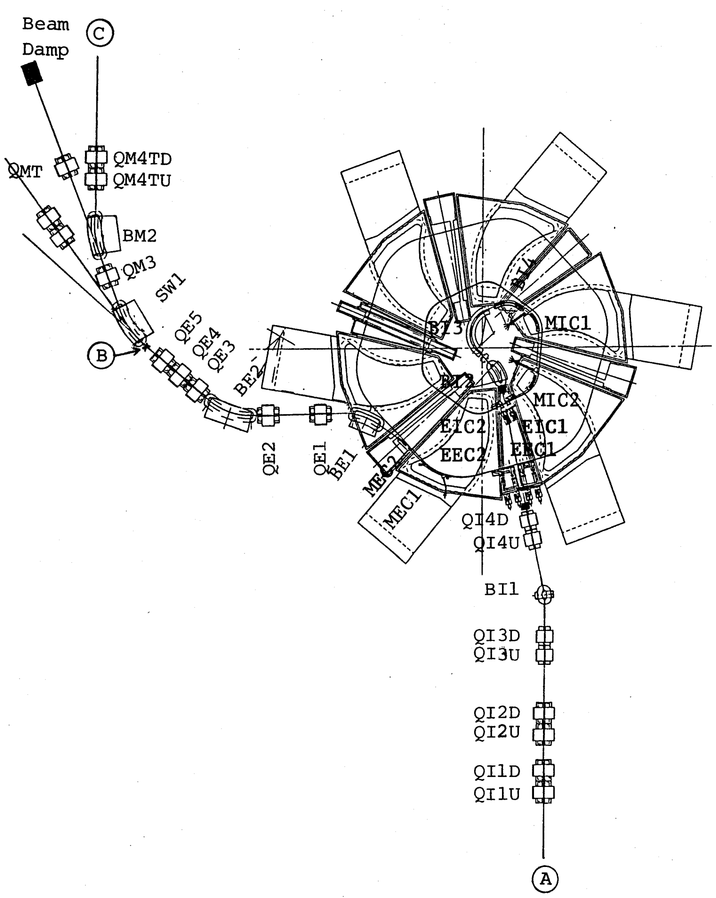

Fig. 1. Schemes of the Injection and Extraction System.

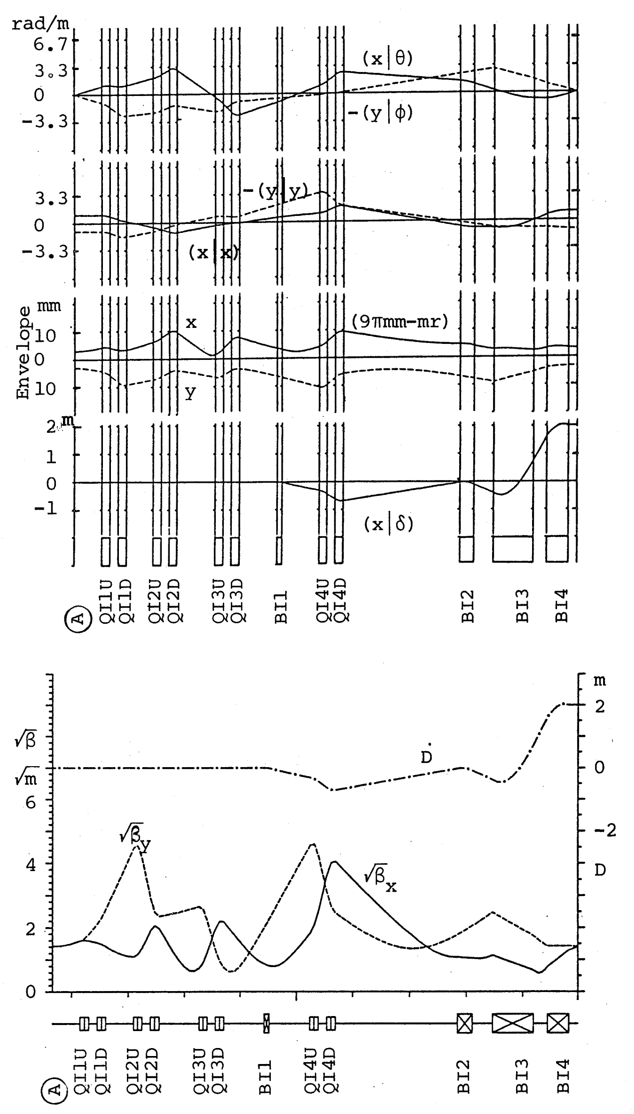

Fig. 2. Optics of the Injection.

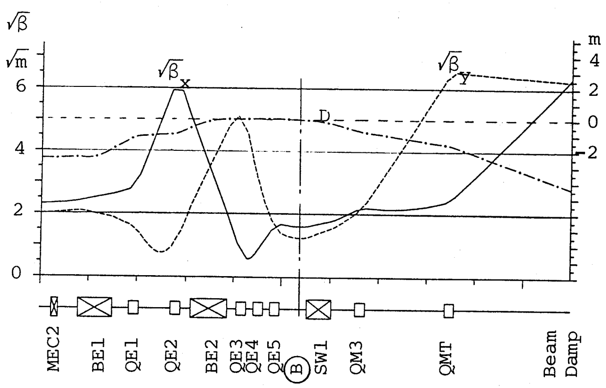

Fig. 3. Optics of the Extraction for tuning of the Ring Cyclotron.

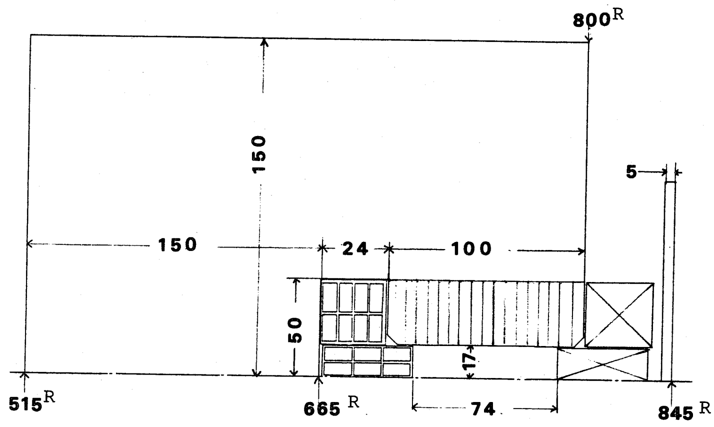

Fig. 5. Cross Section of BI4.

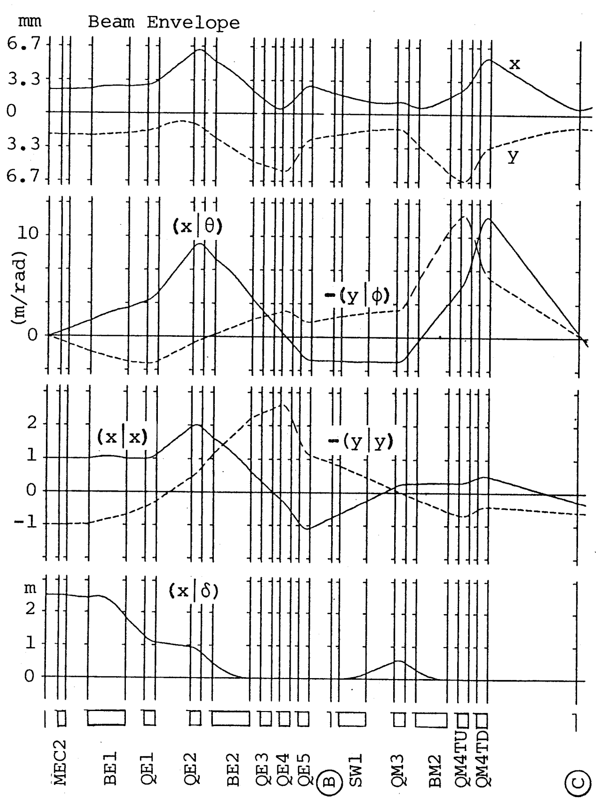

Fig. 4. Extraction Optics for Experiments.

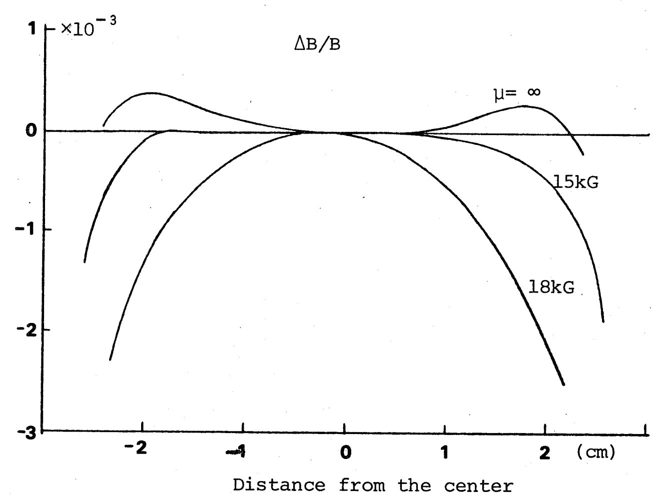

Fig. 6. Calculated Field Distribution of BI4.