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BEAM TRANSPORT SYSTEM FOR HEAVY-ION STORAGE RING -TARN-

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Summary

Beam transport system from the INS-SF cyclotron to the TARN was designed and constructed. The system is composed of optical matching elements, beam monitoring devices and vacuum system. In the present paper, design conception and details of components in the system are described as well as the experimental results of the performance.

1. Introduction

A Test Accumulation ring for NUMATRON project, TARN,[1] was constructed at INS, University of Tokyo. Heavy ions from the SF cyclotron have been injected and stacked into TARN by a combination of multiturn injection and RF stacking method. In order to obtain the efficient injection and stacking of the beam, the emittance in the transverse direction and the momentum spread are expected to be aroud 5πmm·mrad and 2×10^{-3}, respectively. Moreover the orbit characteristics such as the shape of transverse phase spaces and the momentum dispersion function, should be matched to the values required at the injection point of the ring. The matching parameters are not clearly calculated dissimilar to synchrotron case. Then it was necessary to determine the matching parameters at the exit of cyclotron experimentally.

In the present paper, the design principle of the transport system is described first, and the optical elements and the peripherals such as beam monitoring devices are given.

2. Design of Beam Transport System [2]

The optical system of the beam transport line are composed of four sections. They are 1) momentum analyzing section, 2) double achromatic beam section where both the dispersion funciton (η) and its derivative (η') are made to be zero, 3) matching section of the transverse phase spaces and 4) momentum matching section where the dispersion parameters are adjusted to the values required from the optics of the storage ring.

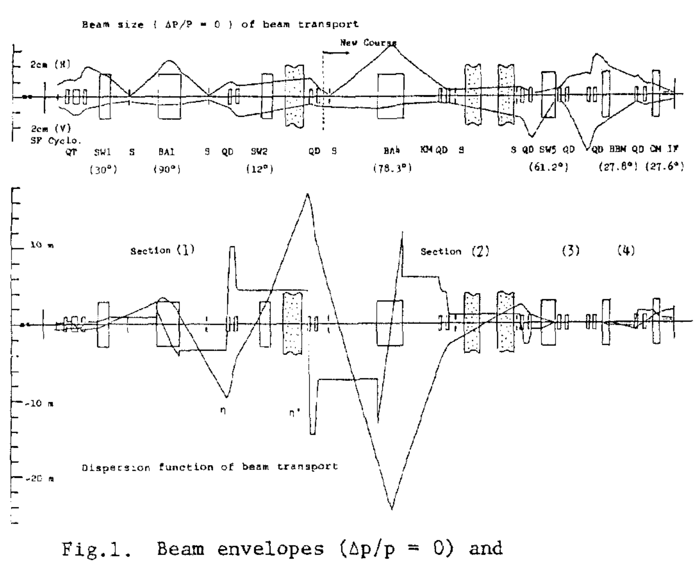

Fig.1. Beam envelopes ($\Delta p/p = 0$) and dispersion functions along the transport system.

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We analyzed the beam optics with the aid of computer program MAGIC.[3] Calculated results of beam envelope and the dispersion function along the transport line are shown in Fig.1.

1st section (momentum analyzing section)

This section consists of the elements from the extraction point of the cyclotron to S4 slits. BA1 analyzer magnet with momentum dispersion of 3.8 m gives the required momentum resolution $\Delta p/p$ of 1×10^{-3} for the RF stacking. The transverse phase ellipses are measured with the 1st emittance monitor EM1 at the extraction point of the cyclotron.

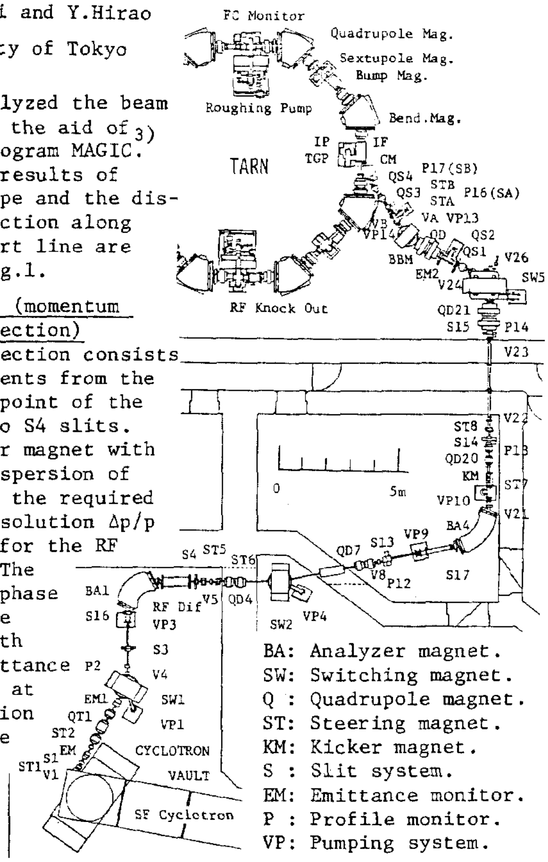

Fig.2.Layout of beam transport system from the SF Cyclotron.

2nd section (momentum matchin section)

Beam line from S4 slits to SW5 is a momentum matching section where the double achromatic beam $\{\eta(H) = \eta'(H) = 0\}$ is produded. Double achromatic beam is made by the use of BA4 analyzer magnet of bending angle of 78.3°, four quadrupole doublets (QD4, QD7, 20, 21) and SW5 magnet of bending angle of 61.2°. Momentum spread (Δp), momentum dispersion function ($\eta(H)$) and derivative of dispersion function ($\eta'(H)$) are measured by the BA4 analyzer magnet with momentum dispersion of 5.2 m, two quadrupole doublets, profile monitors and slit systems. The time structure of incident beam is shaped by the use of two steering magnets, beam dump slit and a kicker magnet which has a deflection angle, a duration time and a maximum repetition rate of 1.25 mrad, 80 μsec and 100 Hz, respectively.

3rd section (matching section of trasverse phase space)

As the beam in 3rd section is double achromatic, four quadrupole magnets (QS1,2, QDA,B) are able to adjust the four parameters of the transverse phase space $\beta(H)$, $\alpha(H)$, $\beta(V)$ and $\alpha(V)$ with required by multiturn injection method. At the injection point of TARN, focused beam size is able to be varied from 2.4 mmϕ to 8 mmϕ. The transverse phase ellipses are measure with the 2nd emittance monitor (EM2) where the effect of the momentum spread can be ignored because of the double achromatic beam.

4th section (momentum matching section

A bending magnet (BBM), two quadrupole magnets (QS3 and QS4) and inflector complex matches the dispersion parameters of the double achromatic beam to the required values, that is $\eta(H) = 1.61$m, $\eta'(H) = 0.36$ at the TARN injection point. The trasported beam are injected to the ring via a magnetic and an electrostatic inflectors. The magnetic inflector gives main inflection

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angle of 27.6°. The electrostatic inflector system of inflection angle of 6.9° consists of two electrodes.

3. General Layout

The layout of the beam transport system is illustrated in Fig.2. The beam is transferred from SF cyclotron to TARN by the distance of about 45 meters. The system is composed of optical matching elements, beam monitoring devices and vacuum system.

The constructed optical matching elements are analyzer magnets (BA1 and BA4), bending magnets (SW5, BBM and CM), ten quadrupole magnets, two electrostatic inflectors, a kicker magnet and steering magnets of six sets. Beam-monitoring devices consist of seven slits of various kinds, an emittance monitor and five profile monitors. The vacuum system is composed of two regular pumping systems, three stages of differential pumping system. The elements of new transport line are shown in table 1.

Table 1. Elements of New Transport Line

General	
Beam energy (for N^{5+})	8.56 MeV/u
Magnetic rigidity	1200 kG.cm
New transport line	25 m
Total length of transport line	45 m
Vacuum pressure	10^{-4}~ 10^{-8}Pa
Optical matching element	
Analyzer magnet	2
Switching and Bending magnets	3
Small and large aperture quadrupole magnets	10
Kicker magnet	1
Steering magnet	7
Electrostatic inflector	2
Beam monitoring device	
Two-dimensional and Beam-dump Slits	3
Beam buffer and Simple slits	4
Emittance monitor	1
Pin-probe and Multi-wire profile monitors	5
Vacuum system	
Regular pumping section	2
Differential pumping section	3
Gate valve for regular and high vacuum	7

4. Magnet Construction and Field Measurement

4-1. Analyzer magnets

The BA4 (BA1) analyzer magnet of orbit radius of 130 cm (95 cm) is a zero gradient field and is an edge focusing type. Designed optics is symmetry for the entrance and exit plane. The bending angle of the magnet is 78.3° (90°) and both the entrance and exit angles are 22.15°. The entrance and exit slits are located at the equal distance of 319.4 cm (190 cm) from the magnet edge. The designed momentum resolution with a 1st order calculation is about 5×10^{-4} (7×10^{-4}) width of entrance and exit slits of 2 mm and for the horizontal emittance of 15 mm.mrad. These resolution are enough for this trasport system of TARN.

The apertures of the analyzer magnets were calculated using the results of orbit calculation. The required useful apertures for BA4 in horizontal and vertical directions are 120 mm (80 mm) and 40 mm, respectively. The whole apertures were decided as 60 mm gap and 140 mm width. The analyzer magnets are of modified window-frame type. The magnets are designed using a computer program TRIM on a basis of the cylindrical model. The maximum field strength in the gap were desiged to be 9.1 KG and 12.4 KG for BA1 and BA4 magnet has the field uniformity $\Delta B/B$ of $\pm 10^{-4}$ ($\pm 2 \times 10^{-4}$) by the computer calculation. Two measured data consistent with each other within an error and it is also in fairly well agreement with the calculated value as shown in Fig.3. The corners of the pole pieces are cut in six steps approximating the Rogowski's curves. Field clamps are attached to fix the fringing fields.

Magnetic field measurement

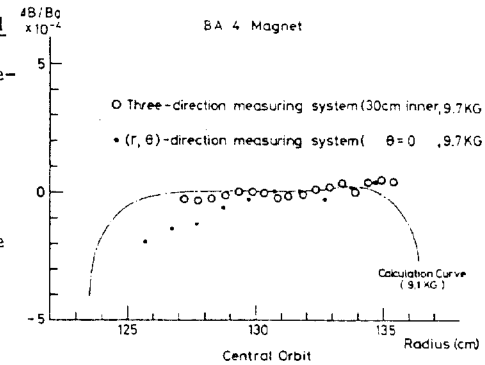


Fig.3 Radial dependence of inner field.

The magnetic field was measured by a Hall probe and an NMR. The magnetic fields of BA4 and BA1 at the flat field region as a function of the exciting current which was measured by an NMR probe. The fringing fields of the magnets are measured with a temperature controlled Hall probe attached to a driving apparatus, which enables the field measurement in a XYZ space, and translations in XY directions are performed by two pulse motors controlled by a mini-computer HP1000. It also processes experimental data; Hall voltage, voltage across the shunt resistor in the current source for the probe, and NMR frequency.

A driving apparatus to move the Hall probe in r-θ directions for the measurement of field strength along the central orbit in BA4. The probe moves to the extent of 105° in azimuthal direction along a guide rail, and 10 cm in radial direction on another guide rail.

4-2. Switching and bending magnets

Two bending magnets play an important role for momentum matching at each end of matching section. The beam with large momentum dispersion in the 2nd section should be changed to double achromatic beam at the end of 2nd section. The matching conditions of SW5 magnet are calculated so that its bending angle is 61.17° with the magnetic radius of 90 cm. Maximum field of SW5 magnet is required as 13.5 KG for the highest energy operation. The magnet was modified and converted from an old magnet. New pole tips are designed so that the orbit radius of 90 cm has a mechanical angle of 57.35°. BBM magnet is used to change a double achromatic beam to a beam with required momentum dispersion. The matching condition of BBM magnet are calculated so that its bending angle and magnetic radius are 27.81° and 104 cm, respectively. Maximum field strength is 11.4 KG for the highest energy operation. The bending magnet was modified and converted from an old magnet. The magnetic fields were measured by two probes of a Hall and an NMR.

4−3. Quadrupole magnets

Following the design of beam transport line, the quadrupole magnets are necessary for the optical matching. The transport design was performed on the assumption that quadrupole magnets have the aperture of 61 mmϕ and the maximum field gradient is 1.6 kG/cm for the narrow beam region and they are 110 mmϕ and 0.8kG/cm for the broad beam region, respectively.

Main features of the small-aperture quadrupole magnets are their strong magnetic field gradients (>1.6 kG/cm) and compactness ($\leq$ 34cmϕ) of the mecnanical structure. The circular pole (R_p = 34.84 mm and R_p/R_g=1.142) circular pole length of magnet is 20cm. The shape of end-cut (6.7 mm × 10.7 mm) was determined so as to enlarge the flat region of the effective focusing strength along the radial direction.

Maximum beam size is calculated to about 70 mm as shown in Fig.1 in the trasport line except in the analyzer magnets. The useful aperture of 90 mm is necessary. The required maximum field gradient is 0.79 kG/cm The distance between the poles are 35 cm (QD21 A and B) and 26 cm (QD A and B), respectively. The pole length of each magnet is 20 cm and bore radius is 55 mm. Field gradients of the magnets are measured at about 0.9 kG/cm at the coil current of 20 A.

Measurement of magnetic field gradient

The absolute values of the field gradient of three kinds of quadrupole magnets were measured by use of the Hall-probe and three-dimensional driving system, which was also used for the analyzer magnet. The field gradients and the higher order component of the field are measured by translating twin coils. The difference between induced voltages in the two coils are detected by a VFC circuit. The radial dependence of sextupole component are shown in Fig.4.

4-4. Other optical elements

Beam pulsing system, injection system of magnetic and electrostatic inflectors and correction magnets are other optical elements.

The pulsing system is composed of a kicker magnet (KM), two steering magnets (ST7), two quadrupole magnets (QD20-A and B) and a dump-slit system (S15). Figure 5 shows the schematic arrangement of them with the calculated beam envelopes. The bending angles at these magnets is 1.25 mrad, and the bending strength is 1500 G cm. The kicker magnet is of H-type made of ferrite. A power supply of a pulseforming network type supplies the magnet with pulsed current of 10μs rise time and 60 μs flat top.

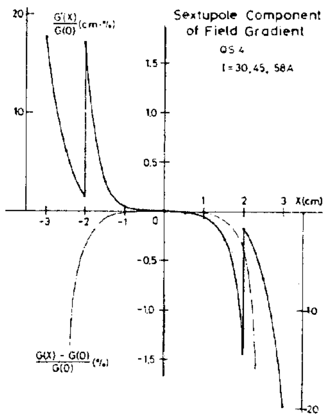


Fig.4 The field gradient and sextupole component of small aperture quadrupole magnet.

The beam is injected to the ring via a magnetic and electrostatic inflectors. The magnetic(CM) has a C-type cross section and gives main inflection angle 27.6° of 108 cm radius. The magnetic field were measured by two probes as Hall and NMR.

The electrostatic inflector system of inflection angle of 6.9° consists of two sets of electrodes and three probes. The septum electrodes are tantalum foil of 0.1 mm thick. The gap of electrodes is designed to be 8 mm, and maximum electric field strength in the gap is 100 kV/cm. The length of each electrode along the beam path is 30 cm.

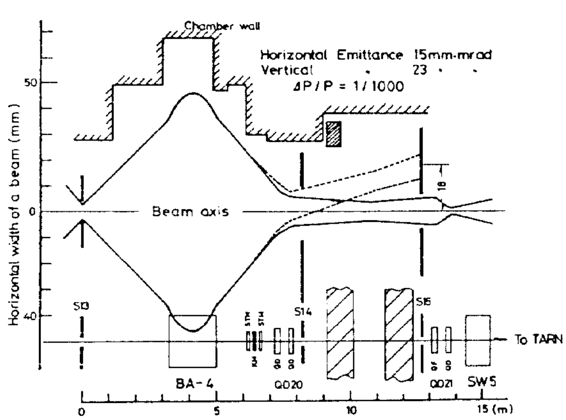


Fig.5 Schematic arrangement of beam pulsing system and calculated beam envelopes. By a combination of the kicker magnet and the steering magnets the beam is pulsed and placed in the orbit to the TARN, as illustrated with solid lines.

Fig.6 Schematic drawing of differential pumping system for the transport line.

5. Monitoring Devices

In the trasport system, monitoring devices consist of various slits, and emittance monitor and profile monitors. The transverse phase ellipses and emittance are measured with the emittance monitor. The momentum spread (Δp), momentum dispersion function (η) and its derivative (η') are measured by the use of the analyser magnets and quadrupole magnets complex and profile monitor.

5-1 Slit system

Accurate definition of objects and images for the optical system is performed by two-dimensional slits. The slit elements are driven by means of axial screws and beam intensity passing through the slits is measured by a beam stopper just after them, which is driven by a pneumatic cylinder. The currents of the slit and the stopper are measured by five current meters.

The buffer slits (S16 and S17) were placed at the front of analyzer magnets (BA1 and BA4).

Simple slit system (SA and SB) are placed at 4th section. The system is composed of slits and stopper and is attached to a frange. Two slits are driven by a remote controlled induction motor.

5-2. Emittance monitor

The emittance monitor (EM2) is placed in the dispersion-free section which measures the shape of transverse phase ellipse and its area (true emittance). The emittance monitor system consists of multi-slits and beam current detector of coaxial pin-probe type. Two signals i.e. position and beam intensity, in the horizontal and vertical directions are recorded on storage oscilloscope or XY recorder. The two signal are also fed to a minicomputer, through ADC circuits, where the beam phase ellipse are calcualted and results are recorded. Emittances of 28 MeV α ion are measured at 12 and 17 mm·mrad respectively for the horizontal and vertical directions.

5-3. Beam profile monitors

Beam profile monitors (P12, 13, 14, 16, 17) are placed upstream of each slit which measures not only the beam profile but also the various parameters of the beam phase space.

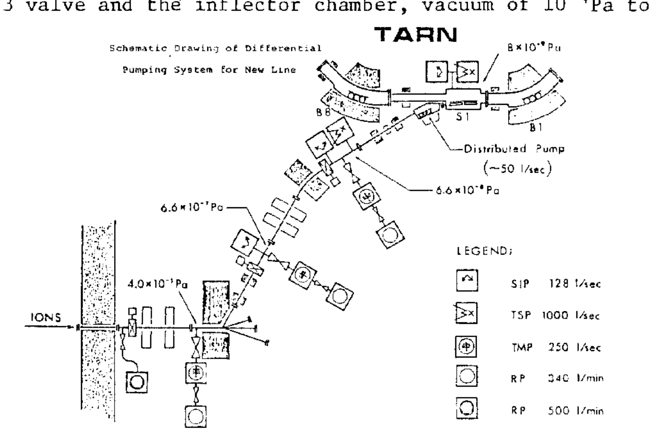
The senser of the monitors (P16 and 17) are placed at the 4 section. The senser of monitor comprizes sixteen 2 mm thick Be-Cu ribbons arranged with a spacing of 1 mm. Electric charges in each ribbons are transferred to condensers in a read-out circuit.

6. Vacuum System

The beam transport line of about 25 m long is evacuated by two oil diffusion pumps and three differetial pumping systems.

The chamber of about 13 m long between V8 and V23 values are designed to be of a regular vacuum region of 10^{-4} Pa. The line is evacuated by two pump stations each of which contains an oil diffusion pump.(VP9 and 10)

In the chamber and duct of about 12 m long between V23 valve and the inflector chamber, vacuum of 10^{-4}Pa to



ultra-high vacuum of 10^{-9}Pa. It is evacuated by three differential pumping stations (VP11,13 and 14). The differential pumping system are shown in Fig.6. The ducts and chambers are made of 316-L stainless steel and their inner surface is processed with chemical etching. They are sealed with metal O-ring. The third differential pumping section is designed to be bakable. The results of operation are shown in Fig. 6, where we can find that the vacuum pressures at the 1st, 2nd and 3rd differential pumping sections and the S1 section of the TARN are 10^{-5}, 10^{-7},$10^{-8}$and 10^{-9} Pa, respectively. In this case, the distributed sputter-ion pump was not operated.

Fig.7 The beam line in the TARN experimental hall

7. Results of Beam Transporting Experiments

Elements for beam transport line were aligned at the positions as shown in Fig. 2. Figure 7 shows the beam line in the TARN experimental hall. In June of 1979, first beam of H_2^+ was transported from the cyclotron to injection point of TARN. Afterwards beam transporting experiments with H_2^+ (14 MeV), He^+ (28 MeV) and H^+ (7 MeV) ions have been performed several times and are now still in progress.

With the use of monitoring devices, beam sizes were measured at various points which is given in Fig. 8 as well as the designed beam envelopes.

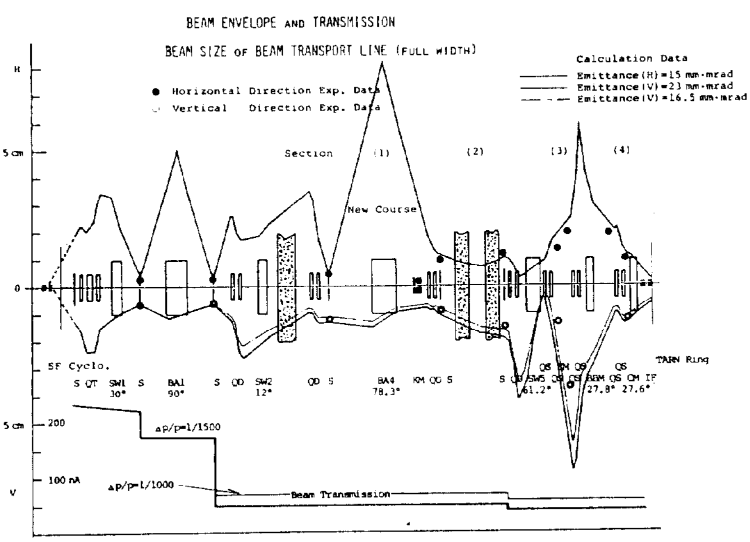


Fig.8 Beam envelopes and transmission of the beam transport line.

In this case, the momentum spread was analyzed to 1/1500 with the BA1 magnet. The tansmitted beam current from S1 slit at the exit of cyclotron to SB slit near the end of transport line, was 17 % and 24 %, corresponding to the momentum spread of 1/1500 and 1/1000, respectively, as shown in Fig. 8. The emittances in horizontal and vertical directions were measured at 12 and 16.5 mm·mrad, respectively (Fig. 9), with the use of EM2 emittancemonitor in the 3rd section. The measured phase ellipses are well consistent with designed ones as shown in Fig. 9.

It is concluded that the beam is transported by the optical elements so that the orbit characteristics well agree with the designed values

8. Acknowedgements

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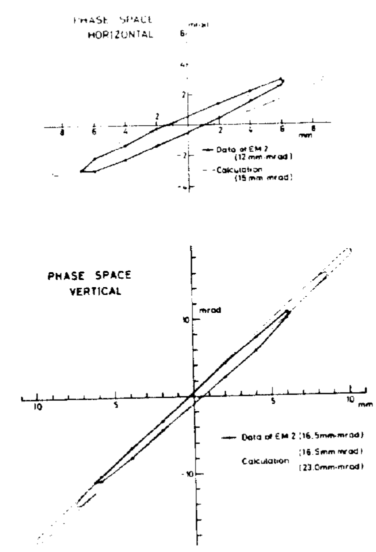

Fig.9 Measured transverse phase ellipses of horizontal and vertical direction with use of EM2 emittance monitor.