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CHARACTERISTICS OF LATTICE AND MAGNET SYSTEM OF TARN II

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Abstract

TARN II is a ring which is designed to be operated both as a synchrotron and a cooler ring for ions. Its mean radius is ~12.4 m and is to be able to accelerate protons up to 1300 MeV and ions with charge to mass ratio of 1/2 up to 450 MeV/u. The ring consists of 24 dipole and 18 quadrupole magnets, which compose the lattice with sixfold symmetry for synchrotron acceleration (Synchrotron Mode) and another one with threefold symmetry to realize doubly achromatic sections for beam cooling (Cooler Ring Mode). These modes can be transferred between each other keeping the operating point at the position of $(\nu_H, \nu_V) \sim (1.75, 1.25)$. The acceptance for beam cooling experiment at TARN II is expected to be improved from 70π to 400π mm·mrad by application of pre-cooling of horizontal betatron amplitude by stochastic method with Synchrotron Mode before moving to Cooler Ring Mode. Main magnets of the ring with AC characteristics have already been fabricated. Dipole magnets with H-type are found to have realized required good field region of ±100 mm from the result of static field measurement.

Introduction

Recently, needs for high Energy Heavy Ion Beam have been increasing more and more not only for nuclear physics but also for other applications as medical use. At Institute for Nuclear Study, University of Tokyo(INS) a storage ring for low energy ion beam (TARN) has been operating since Aug. of 1979 so as to develop the accelerator physics and technology related to ion beam accumulation[1]. Further the momentum spread of the RF stacked beam has been decreased by stochastic cooling with notch filter[2]. However, from limitation due to DC charcteristics of dipole magnets, developments related to synchrotron acceleration are left to be studied in future and rather limited length of straight sections (1.8m) has prevented us from installing larger equipments for beam ejection and electron beam cooling and so on. Cooling techniques with stochastic method or electron beam are originally invented in connection with high energy particle physics[3,4], but in recent years, these methods have also attracted much interest among nuclear physisists for precise experiment which utilize a cooler ring[5].

So as to provide a facility to respond to these needs, a larger ring called TARN II with AC characteristics is designed and is now under construction. As the injector for TARN II, the SF cyclotron is assumed for the time being, which will be replaced in the near future by an injector linac system partially under construction now[6]. Main parameters of the magnetic focusing system of TARN II is given in Table 1 and layout of TARN II is shown in Fig. 1.

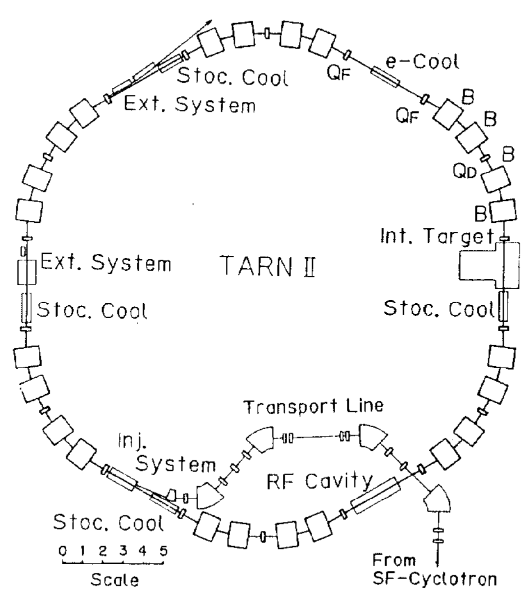

Fig. 1 Layout of TARN II.

Lattice Design

The focusing structure of TARN II ring is designed based on a simple FODO lattice because of its compactness so as to realize the higher maximum energy in rather limited site. Long straight sections are made by inserting drift spaces 4.26 m in length between horizontally focusing quadrupole magnets at every unit cell and the unit cell coincides with the superperiod. The whole circumference is composed of six unit cells. For usual synchrotron acceleration, these cells are all excited identically resulting regular structure of Twiss parameters and dispersion function with small maximum

Table 1

Magnetic focusing system of TARN II

Maximum Magnetic Rigidity		68.75 kG·m
Average Radius		12.38 m
Circumference		77.76 m
Radius of Curvature		3.82 m
Focusing Structure		FBDBFO
Repetition Rate		1/2 Hz
Maximum Field of Dipole Magnet		18 kG
Maximum Field Gradient of Quadrupole Magnet		70 kG/m
Number of Dipole Magnets		24
Number of Quadrupole Magnets		18
Length of Dipole Magnet		1.00 m
Length of Quadrupole Magnet		0.20 m
Superperiodicity		
Synchrotron Mode		6
Cooler Ring Mode		3
Transition Gamma		
Synchrotron Mode		1.86
Cooler Ring Mode		2.97
Betatron Tune Value	Horizontal	Vertical
Synchrotron Mode	~ 1.75	~ 1.75/1.25
Cooler Ring Mode	~ 1.75	~ 1.25

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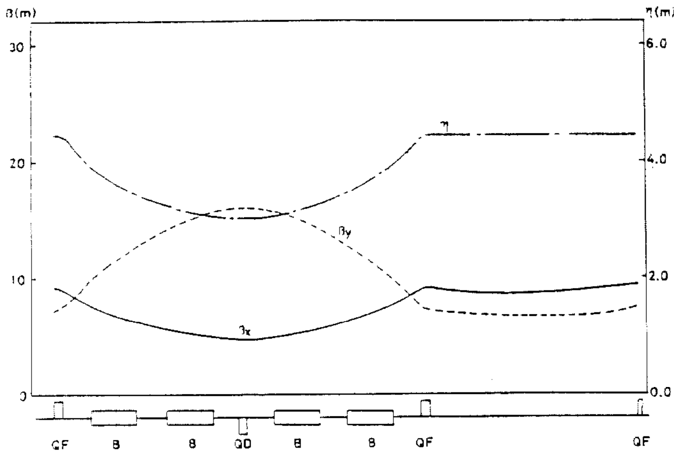

Fig. 2 Beta and dispersion functions of TARN II Synchrotron Mode with ν-values of 1.75 and 1.25 in hori. and vert. directions, respectively.

β-values as shown in Fig. 2, which is preferable from the point of view of increasing machine acceptance (Synchrotron Mode). In fact designed acceptance of Synchrotron Mode is as large as 400π mm·mrad. The rather higher superperiodicity of six is also beneficial to avoid sector resonances in choosing the working line. However for this excitation mode, every long straight section has finite dispersion as large as ~5 m, which seems to be unsuitable for momentum cooling because transverse emittance blow up is anticipated during momentum correction process. So as to realize doubly achromatic section required for momentum cooling equipment together with finite dispersion section needed for internal target position, superperiodicity of the lattice is reduced to three by changing only excitation pattern of quadrupole magnets (Cooler Ring Mode). If the arrangement of magnets is made to have mirror symmetry with respect to point B in Fig. 3, the condition to make the straight section just outside of points A and C to be doubly achromatic is given by

$$f = 0, \tag{1}$$

if we denote the transfer matrix, M, from point A to B as

$$M = \begin{pmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{pmatrix}. \tag{2}$$

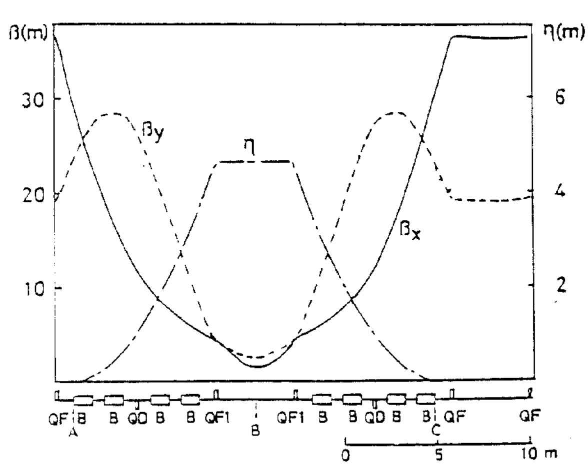

Fig. 3 Beta and dispersion functions of TARN II Cooler Ring Mode. ν-values are chosen at ~1.75 and ~1.25 for horizontal and vertical directions, respectively. One third of the circumference is shown in the figure.

The numerical calculation of Twiss parameters is executed with use of computer code SYNCH[7]. For the operation point of (1.75, 1.25), the beam size is made small at the internal target position, but β-functions at cooler section are rather larger ($\beta_H \sim 36$ m, $\beta_V \sim 20$ m), which will reduce the machine acceptance of the Cooler Ring Mode to 70π mm·mrad.

Operation Mode

At TARN II, two modes of lattice structure are to be provided as described in the previous section. Synchrotron Mode is excited with repetition rate of 1/2 Hz with the pattern as is shown in Fig. 4(a). For this mode, beam is to be multi-turn injected up to 400π mm·mrad and after RF capture it is accelerated in 750 msec. and finally it is slow ejected by resonant extraction method during 450 msec[8]. As the transition energy of this mode is ~810 MeV, we must take care of crossing the transition when we want to accelerate protons to higher energy than this energy.

For cooling experiment with either stochastic or electron beam method, fairly long cooling time is needed and longer flat top is to be provided for Cooler Ring Mode. The maximum field is limited at the lower value of ~15 kG corresponding to the proton energy of 1000 MeV to suppress the power consumption of high duty operation. The typical excitation pattern of this mode is given in Fig. 4(b). This mode aims at good quality beam somewhat sacrificing beam intensy because available size of transverse phase space is decreased due to larger maximum β-values as described before.

In the Cooler Ring Mode, three degrees of freedom is provided by three family of quadrupole magnets, Q_F, Q_D and Q_{F1}, while one constraint given by Eq.(1) is imposed to realize doubly achromatic section and other two degrees of freedom are used for tuning ν-values in horizontal and vertical directions. So it is possible to find out a variety of solutions keeping the operating point at (1.75, 1.25) if we remove the doubly achromatic condition as shown in Fig. 5. In the figure, point A corresponds to the Cooler Ring Mode and point B, where G_F and G_{F1} are equally excited, corresponds to Synchrotron Mode with superperiodicity of 6. It is seen these two modes can be connected between each other with continuous change of excitation currents of three family

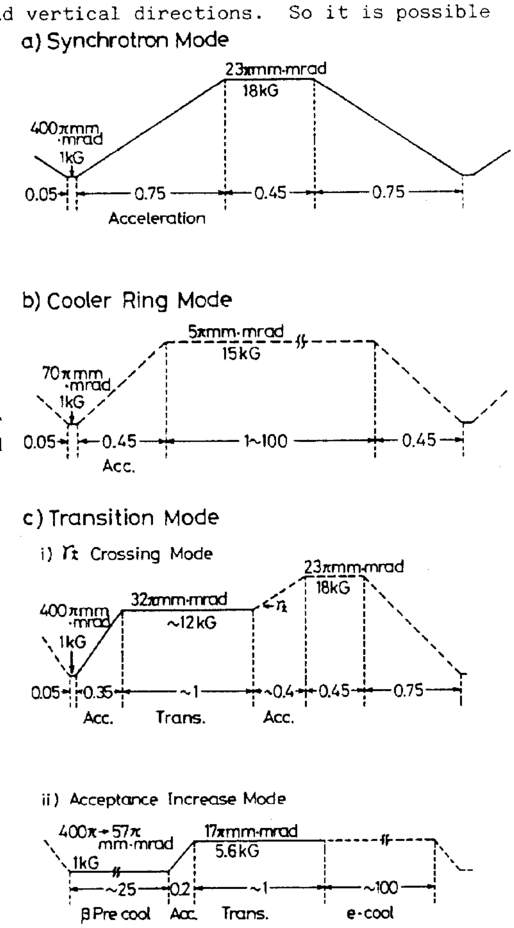

Fig. 4 Operation Modes of TARN II.

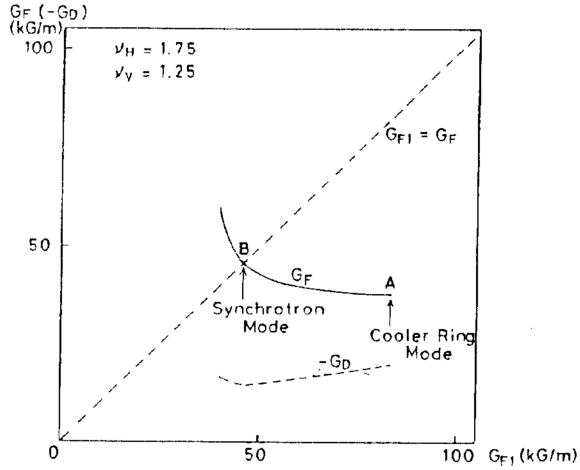

Fig. 5 Field gradients of three family of quadrupole magnets during transition between Synchrotron and Cooler Ring Modes.

of quadrupole magnets. In Fig. 6, maximum values of beta and dispersion functions for these solutions are given. No serious enlargement of beam envelope is anticipated during this transition between these two modes. So Transition Mode from Synchrotron Mode to Cooler Ring Mode keeping circulating beam in the ring is proposed as shown in Fig. 4(c). One of the merit of this Transition Mode is possibility to remove the problem related to the acceleration across the transition energy for the case of proton(γ_t Crossing Mode). Due to the fact that average value of dispersion throughout the whole circumference for Cooler Ring Mode is almost half of that of Synchrotron Mode, the transition energy of Cooler Ring Mode is much higher (1850 MeV) than the maximum energy of TARN II (1300 MeV). If proton is accelerated up to the energy just below the transition energy of Synchrotron Mode (810 MeV) and then the magnetic focusing structure is shifted to Cooler Ring Mode, beam acceleration through this energy region can be made with usual manner without such complex technique as γ_t-jump. Compared with acceleration by Cooler Ring Mode from the begining, the acceptance in transverse phase space can be made larger and higher superperiodicity of 6 can be used for early stage of acceleration, where beam might be more unstable compared with later stage after shrinkage of beam size. The other merit of such transition is of course increase of the acceptance (Acceptance Increase Mode). As the electron beam size for electron beam cooling is 50 mm in diameter[9], beam emittance should be less than 17π mm.mrad in order to apply electron beam cooling. For the condition of accelerating protons from the injection energy of 7 MeV to 200 MeV, beam emittance shrinks from 57π mm.mrad to 17π mm·mrad assuming conservation of normalized emittance. So if multi-turn injection is applied with Synchrotron Mode up to 400π mm·mrad, then betatron pre-cooling by stochastic method is needed to cool down the emittance to 57π mm·mrad before acceleration. Thus acceptable beam intensity into the ring is expected much increased.

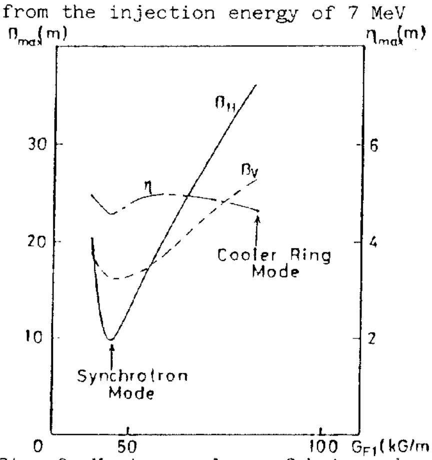

Fig. 6 Maximum values of beta and dispersion functions during transition between two modes.

Assuming bandwidth of 300 MHz at frequency region around 1.5 GHz, where almost perfect mixing is expected, and cooling of the preamplifier system to 77°K liquid nitrogen temperature, cooling time for transverse pre-cooling above mentioned for 7 MeV proton with beam intensity of 10^8 is estimated at ∿20 sec. from the well known relation[10]

$$\frac{1}{\tau} = \frac{W}{2N} \cdot \frac{\sin^2\mu}{M + U} , \qquad (3)$$

where W, N, M and U represent bandwidth, beam intensity, mixing factor and the ratio of the amplifier noise to the signal power, respectively and μ is the phase advance of betatron oscillation between the pick-up and the kicker. Transition to Cooler Ring Mode is to be made after acceleration and beam size has already shrunk as shown in Fig. 4(c). Such combination of stochastic cooling with electron beam cooling is considered to increase the utility of the cooler ring as TARN II so much[11].

Magnet Design

Main magnet system of TARN II ring consists of 24 dipole and 18 quadrupole magnets. Assuming the beam emittances after multi-turn injection to be 400π and 10π mm·mrad in horizontal and vertical directions, respectively and fractional momentum spread of ±0.22 %, required useful apertures for the case of Synchrotron Mode are estimated at 200 x 50 mm² and 185 x 60 mm² (Hori. x Vert.) for dipole and quadrupole magnets, respectively. Reflecting the fact that maximum values of beta functions are larger for Cooler Ring Mode, the horizontal beam emittance after multi-turn injection should be limited below 70π mm·mrad. Remedy for this situation has been already discussed in the previous section but vertical useful aperture is enlarged to 60 mm also for dipole magnets considering the case where Cooler Ring Mode is applied from the begining without Transition Mode. So the magnet gap is chosen at 80 mm taking into account additional spaces necessary for vacuum chamber wall and heat insulator material for baking process to attain ultra-high (∿ 10^{-11} Torr) vacuum.

As the ring is AC operated with repetition rate of 1/2 Hz for Synchrotron Mode and dB/dt amounts to ∿2.3 T/sec. for dipole magnet, the magnets should be made of stacked laminated steel so as to suppress the effect of eddy currents. Quadrupole magnets in the present TARN are already made of laminated cores 0.5 mm in thickness and they are to be used as the focusing elements of TARN II. Six quadrupole magnets are newly fabricated to hold sixfold symmetry. Its bore raius is 65 mm and the pole shape is hyperbola smoothly connected to its tangential lines at both sides, which is almost identical with ones in the present TARN[12].

H-type is adopted for the type of the dipole magnets to be newly made. Although window-frame type has the merit of good field homogeneity and compactness, coils are located at positions where magnetic field is so high that relatively larger eddy currents in the conductor of coils are anticipated for this type. C-type magnet is convenient to access to the vacuum chamber, but the size of this type becomes considerably larger and there might be some problem in mechanical strength considering our gap size of 80 mm. The size of H-type magnet is moderate and its coils are located at positions with relatively lower magnetic field. Coils are shielded from the region of beam location by iron pole for H- and C-types and field structure in the beam region is, in general, insensitive to the coil arrangement error. For window-frame and H-types, reflection symmetry with respect to the central line in radial direction exists and quadrupole and octapole components are suppressed and only such components originated by fabrication error can appear. From the above consideration, H-type is considered to be superior to other types for the present case.

The dipole magnet is decided to be made by straight shape because of its easiness of fabrication and flexibility for further conversion to a larger ring. Its length is suppressed at rather shorter value (1 m) to reduce the sagitta at reasonable value(16.4 mm). The pole edges are shaped with B constant curve[13] to realize the uniform field in the wide region of ± 100 mm in radial direction and for wide range of excitation level up to 18 kG. Small shims connected smoothly to the B constant curve at both sides as shown in Fig. 7 are attached so as to modify the field structure which tends to fall down at both sides due to saturation of iron at higher fields. The shape of the shim is determined based on the numerical calculation with use of the computer code TRIM[14].

As the material of the laminated core, cold rolled silicon steel strip (S23 in Japanese Industrial Standard) with special heat treatment is adopted. It is 0.5 mm in thickness and surface coated by an inorganic insulation layer. Rogowski's end cut shaping[15] is applied at both ends of the magnet with approximation of three steps so as to suppress the variation of the effective field boundary depending on the excitation level.

Field Measurement of the Dipole Magnet

The static field structure of the dipole magnet has been studied with the available DC power supply at lower field level up to ∿2.5 kG. A temperature controlled Hall-probe (Siemens FC 33) with a dimension of 3 x 6 mm² has been used for field mapping. The position of the probe is automatically controlled with driving mechanism composed of ball screws and pulse motors in a horizontal plane[16]. Its vertical position is set mannually before starting the measurement. Data taking has been made with a 16 bits microcomputer with CAMAC interface. The stability of the power supply is better than 1×10^{-4} and further the effect of the current variation is monitored with an NMR probe which is positioned at a fixed place in the central part of the magnet with good field homogeneity throughout the mapping process. In Fig. 8, the dipole magnet under field measrement is shown.

The measured field structure in radial direction is shown in Fig. 9 together with that of the computer calculation with TRIM. In the figure, also shown are measured distribution of the effective length and integrated field strength ($\int Bds$) along the magnet axis. It is seen that good field region of ± 100 mm is

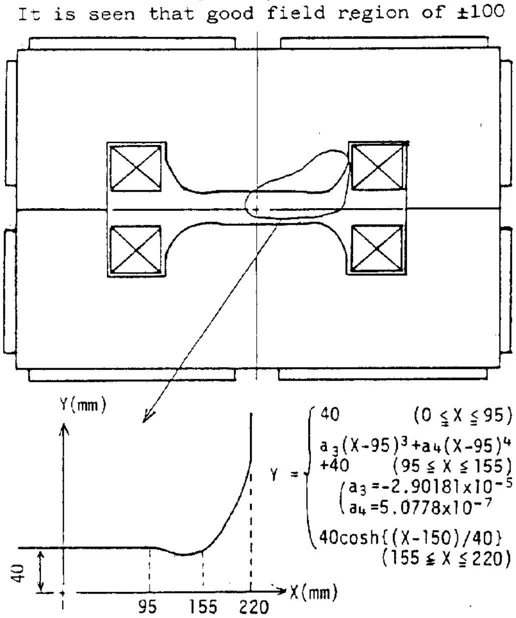

Fig. 7 Cross sectional view of the dipole magnet.

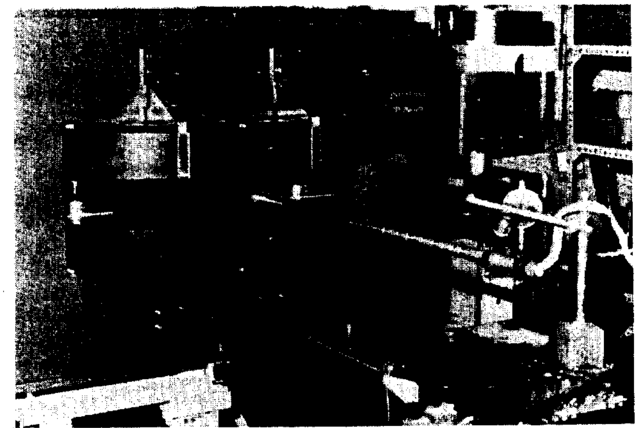

Fig. 8 Dipole magnet of TARN II under field mapping.

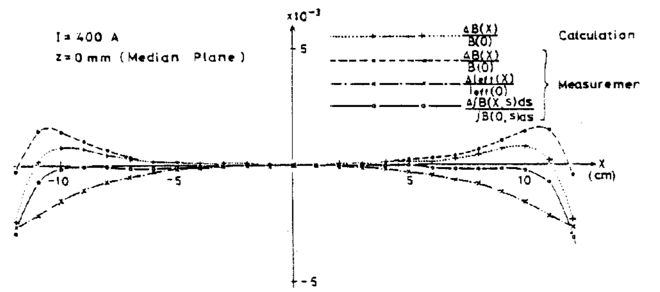

Fig. 9 Radial field distribution of the dipole magnet.

attained. The effect of the shim can well cancell the variation of the effective length. However the results so far taken are limited only lower excitation level due to limitation of available power supply. Magnet quality at higher fields and AC characteristics are soon to be measured with a new power supply with full and AC excitation capability, which is under construction oriented for field measurement.

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