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INITIAL OPERATION OF COOLER RING, TARN II

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Abstract

TARN II is a heavy ion cooler synchrotron for the studies of accelerator, atomic and nuclear physics, presently being constructed at the Institute for Nuclear Study, University of Tokyo. Its maximum energy is 370 MeV/u for the ions of a charge to mass ratio of q/A = 0.5, corresponding to a magnetic rigidity of 6.1 T·m. The circumference is 77.76 m, just 17 times the extraction orbit of injector cyclotron. Six long straight sections, 4.20 m in length each, are used for the beam injection, extraction, electron cooler and RF accelerating cavity, respectively. At the beginning of 1989, the first experiment of beam injection has been performed successfully with use of 28 MeV α particles. In this paper, the status and initial results of operation of TARN II are presented.

Introduction

After the final experiment of stochastic cooling, we disassembled the old TARN and started the construction of new ring, TARN II in 1986[1]. It is an experimental facility for accelerator, atomic, and nuclear physics with an electron cooler equipment as well as the beam acceleration and slow extraction functions. This cooler synchrotron has the maximum magnetic rigidity of 6.1 T·m, corresponding to a proton energy of 1.1 GeV. The main parameters of the ring are shown in Table 1. The ring is hexagonal in shape with an average diameter of 24.8 m. Its circumference is 77.76 m and was chosen to be 17-times that of the extraction orbit of the injector SF cyclotron. It has 6 long straight sections of 4.2 m length each. These are used for the beam injection system, an RF cavity, an electron cooling device, and an slow beam extraction system. It takes 3.5 sec for the power supply to excite the whole magnet system to full excitation. The flat top duration of magnetic field is variable and sufficiently long for beam cooling and extraction. The RF cavity can be tuned from 0.5 to 8.5 MHz and the power amplifier can produce a gap voltage of 2 kV. The electron cooling system can cool the ion beam with energy of up to 200 MeV/u. It consists of an electron gun, an interaction region of 1.5m in length, collector and electron guiding coils.

At present, all ring system are completed, including the extraction system. The first trial of beam injection was performed in December 1988, and α beams of 28 MeV were circulated in TARN II. Subsequently the beam injection experiments have been performed several times for the investigation of multi-turn injection and beam monitoring system. On the other hand the off-line test of e-cooling has been successfully performed[2]. Beam acceleration and cooling experiments are scheduled in the beginning of coming summer. In the present paper, the main feature of the ring is presented as well as the results of first beam experiments.

General Description of TARN II

Beam Transport Line

The new transport line in the TARN II room is composed of 4 window-frame type bending magnets, a C-type magnet, 2 pairs of quadrupole doublets, 4 quadrupole singlets, a quadrupole triplet, 2 pairs of

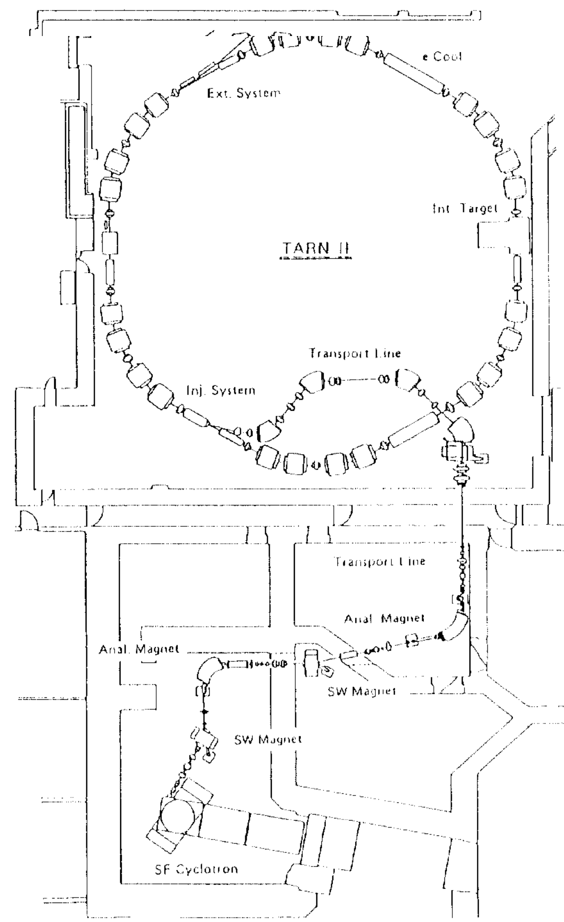

Fig. 1 Layout of TARN II and SF cyclotron

TABLE 1

Main parameters of TARN II ring

Maximum magnetic rigidity		6.1 T·m
Max. beam energy	proton	1.1 GeV
	ions with q/A=1/2	370 MeV/u
circumference		77.76 m
average radius		12.376 m
radius of curvature		4.045 m
focusing structure		FBDBFO
length of long straight section		4.20 m
superperiodicity	acceleration mode	6
	cooling mode	3
rising time of magnet excitation		3.5 sec to full
repetition rate (max.)		0.1 Hz
max field of dipole magnets		15.0 kG
max gradient of quadrupole magnets		70 kG/m
revolution frequency		0.31 - 3.75 MHz
acceleration frequency		0.62 - 7.50 MHz
harmonic number		2
max rf voltage		2 kV
useful aperture		50 x 200 mm²
vacuum pressure		10^{-11} Torr

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steering magnets (1 pairs for horizontal adjustment and 1 for vertical) and an electrostatic inflector. These optical elements make the matching condition of two families of Twiss parameter at the extraction point of the cyclotron and the injection point of TARN II. The double achromatic section is prepared between two dipoles (B2 and B3) for the easy adjustment of matching condition. The beam monitoring system in the line comprises four slit-stoppers, two profile monitors, an emittance monitor and two rod stoppers which measure the beam current and beam profile simultaneously. In addition, a beam profile monitor of quartz plate has been placed at the entrance of inflector.

Magnet System

The focusing structure of the magnet system is based on a FODO lattice, and the long straight sections are prepared by inserting drift space of 4.20 m length between horizontally focusing quadrupole magnets at every unit cell. The whole circumference is composed of six unit cells. For the synchrotron acceleration mode, these cells are excited identically and the dispersion function and the maximum β-value can be kept small which results in the large machine acceptance, 400π mm · mrad. On the other hand, to realize the zero dispersion straight section for the momentum cooling, the superperiodicity is reduced from six to three with the change of excitation current of quadrupole magnets. In this cooler ring mode, the maximum β-value becomes large and the acceptance is reduced to 140 π mm · mrad. These two modes are transferable each other, keeping the operating point at the same position in the tune diagram.

The excitation of current for the magnets are performed with four power supplies, one for the dipole magnets and three for the quadrupole magnets. The current and voltage patterns for the bending magnets at their maximum rating in the synchrotron mode are given in Fig. 2. The current pattern is a trapezoid wave form with a repetition rate of 0.1 Hz and the rising period is 3.5 sec.

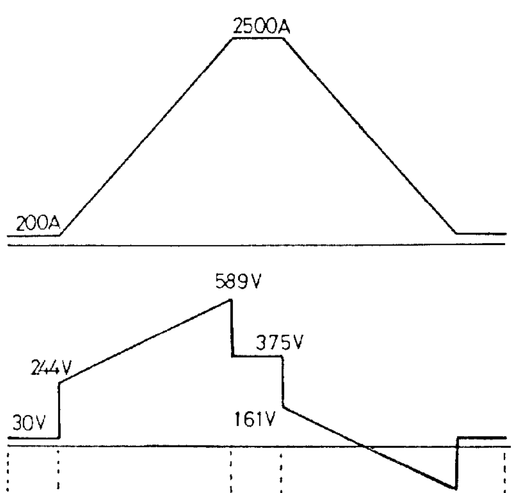

Fig. 2 Current pattern of bending magnet at the maximum rating in the synchrotron mode.

Vacuum System

The materials of the vacuum chambers mainly comprise 316L stainless steel and pure alumina ceramics. At the center of each twin dipole magnet, either a sputter ion pump (800 or 400 l/s) or a titanium sublimation pump (100 l/s) is installed. The inflector chamber and the chamber at the crossing point of the main ring with the beam injection line are especially evacuated by sputter ion pumps of 800 l/s. The auxiliary pumping systems comprise a 500 l/s turbomolecular pump, a mechanical booster pump and a rotary pump, located at two long straight sections (S3 and S5) and at the inflector chamber. For the beam injection line the vacuum system comprises 4 turbomolecular pumps, 3 sputter ion pumps and 4 titanium sublimation pumps. Presently, both the ring and the beam injection line are evacuated with only turbomolecular pumps and the baking process has not yet been tried. Pressure at the pump head is around several times 10^{-9} Torr while the average pressure in the chamber is one order worse than this value. The main component of residual gases is H_2O. A final pressure of the order of 10^{-11} Torr will be realized upon operating the sputter ion pumps and sublimation pumps after a high-temperature bake-out.

RF Acceleration and Beam Monitoring System

An RF system accelerates the ions from the injection energy to the working energy. The lowest injection energy among the various ions from the SF cyclotron, is 2.58 Mev/u for Ne^{4+} corresponding to the revolution frequency of 0.307 MHz. At the top energy of 1100 Mev, the revolution frequency is 3.5 MHz and the RF frequency ratio of the initial and final stages is thirteen. The harmonic number is chosen as two and the designed acceleration frequency changes from 0.6 MHz to 7 MHz. An RF voltage of 2 kV is adequate for the acceleration of the beam with the momentum spread of 0.5 % within the acceleration period of 3.5 sec. This RF voltage is produced using a cavity loaded with ferrite 2.5 m long. In this cavity, the resonance frequency has been successfully varied by a factor of 13 with the change of ferrite bias current from 0 to 750 A.

The low level RF electronics system controls the frequency and amplitude of RF field, and the automatic tuning of the cavity. Functional shapes of the RF frequency, cavity voltage and bias currents are produced with the use of a personal computer PC9801, three memory modules and three DAC's. Data in memory modules are read out at every increment of the magnetic field strength through a B-clock signal. The heart of the system is a voltage controlled osciliator, the RF frequency of which is produced according to a sum of the function voltage from the memory modules and signals from the beam position (Δ R) and beam phase ($\Delta\phi$) monitors. With the aid of this feed-back loop, the RF signal can always be phase-locked with the circulating beam bunch in the ring. At the injection period, however, the RF frequency is phase-locked with the synthesizer signal, which is adjusted by the operator in the control room. The RF amplitude is modulated according to the calculated function signal and the envelope signal in the cavity. All components, including the high power parts, are controlled by the central computers, through the serial highway of CAMAC system.

At the straight sections, many kinds of beam monitoring devices are are installed. As destructive monitors three beam profile-and-current monitors with use of quartz plate which is hit by the ion beam and the lighted portion of the quartz are viewed with TV camera through the glass flanges, a scintillation and two rod beam profile-and-current monitors which moves horizontally from the inner side and scrapes off the beam and measures the beam profiles. Non destructive beam monitor system comprises the six electrostatic beam position monitors distributed along the ring, a permalloy core monitor as a DC current transformer, a Schottky signal monitor of travelling wave type and two phase monitors for the RF feedback control.

Slow Beam Extraction

The accelerated and cooled heavy ion beams are to be slowly extracted utilizing the third integer resonance. The extracted beam energy is required to be variable over a wide range from 150 MeV/u to 370 MeV/u. Thus, the beam extraction must be performed for a circulating beam with a rather large emittance (60π mm·mrad). To respond these requirements, high-efficient extraction method was proposed with use of rather complicated adjustment of the current of dipole magnet and quadrupole magnet[3]. In viewing this scheme as a final goal, as a first trial of the extraction, a simple extraction method has been in progress where a sextupole magnet is used for resonance excitation, three bump fields for the closed orbit distortion and tunes are varied from (1.75, 1.80) to (1.667, 1.80) with the change of quadrupole magnet currents. Parameters of slow extraction system are given in Table 2. In this scheme, the sextupole fields is dc excited and it can be seen from the simulation results that the beam safely circulates on an ellipse, even with an existence of nonlinear sextupole field at the injection energy. An electric septum, 70 kV/cm and 1.0 m long, was located in the second straight section and the first septum magnet, 5 kG in magnetic field strength and 1.0 m long, was at the third straight section[4].

TABLE 2

Parameters of slow extraction system

Ion Species	p, α , C, and Ne
Beam Energy	150 MeV/u ~ 370 MeV/u
Extraction Scheme	1/3 resonance
Operation Point	(1.66667, 1.80)
Septum Position	75 mm outside from the central orbit
Beam Emittance	
Circulating Beam	63π mm · mrad
Extracted Beam	5π mm · mrad
Momentum Spread	0.2 %

Results of First Beam Experiment

In the fall of 1988, the first trial of beam transport from the SF cyclotron to the TARN II ring, was performed with use of 28 MeV α beams. At the exit of the cyclotron, the beam emittance was measured at 15 π mm · mrad (horizontal) and 20π mm · mrad (vertical), respectively and the momentum spread was 0.2%. In this experiment, the time structure of beam was continuous wave and the average current was 1 μA. The one third of the beam was transported to the injection point of the TARN II ring, through the whole transport line of 40 m length.

After this successful trial of beam transport, the first experiment of multi-turn injection in the ring was carried out at the beginning of 1989. In this case, the cyclotron accelerated the pulsed beam of 28 MeV α particles. The pulse width and the repetition rate were 1 msec and 30 Hz, respectively. The peak current at the exit of cyclotron was 3 μA and that of

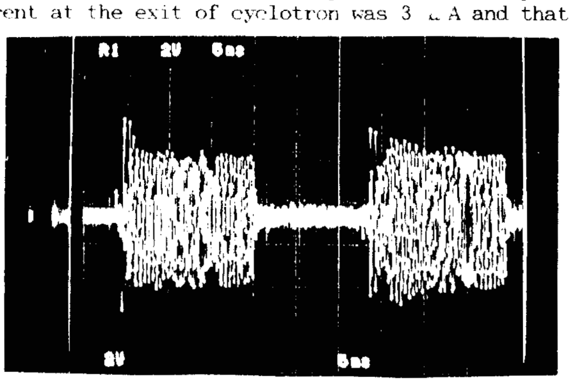

Fig. 3 Signals from the electrostatic beam monitor. Beam injection was performed with 30 Hz. The horizontal and vertical scales are 5 ms/div and 2V/div, respectively.

the transported beam to the ring was 1 μA. After passing through the electrostatic inflector with voltage of 41 kV, the beam was multi-turn injected in the ring with the excitation of two bump magnets for the distortion of closed orbit. The decay time of bump fields were adjusted to 40 μ sec, around 20 times of revolution period of the beam in the ring. Then the injected beam was adiabatically captured by the RF fields, 500 μ sec after the multi-turn injection. The frequency of RF field was adjusted to maximize the capture efficiency. In Fig. 3 the signal from the electrostatic beam monitor was given. The amplitude of RF field was modulated so as that the width was 15 msec. Then the signal disappeared suddenly at 15 msec after the beam injection. The life time of the stored beam was measured at 0.75 sec with use of the beam signals from the Intermediate Frequency (0.455 MHz) amplifier. Its signal was displayed on the spectrum analyzer whose central frequency was adjusted to IF. The life time was determined mainly by the residual gas pressure in the ring of around 10^{-8} Torr. The vacuum chamber was not yet baked out and the three turbo molecular pumps were used for this experiment. In Table 3, the results of first beam experiment were summarized.

TABLE 3

Results of first Beam Experiments

Ion beam	$^4He^{2+}$
Ion energy	28 MeV
Number of stored ions	10^8
Life time	750 ms
Pressure	10^{-8} Torr
RF frequency	7.984 MHz
Harmonic number	17

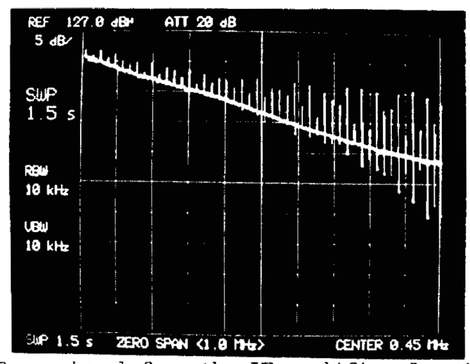

Fig. 4 Beam signal from the IF amplifier for the life time measurement. Scales are 0.15 sec/div (Horizontal) and 5dB/div (Vertical).

Acknowledgement

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