PRESENT STATUS OF COOLER SYNCHROTRON TARN II

T. KATAYAMA, K.CHIDA, T.HATTORI[*], T. HONMA, M.KANAZAWA[**],
A. MIZOBUCHI, M. NAKAI, A.NODA, K. NODA, M. SEKIGUCHI, F. SOGA,
T. TANABE, N. UEDA, S. WATANABE, T. WATANABE AND M. YOSHIZAWA

Institute for Nuclear Study, Univ. of Tokyo
Midoricho, 3-2-1, Tanashi, tokyo 188, Japan

[*] Tokyo Institute of Technology
[**] National Institute for Radiological Science

Abstract

A cooler synchrotron TARN II has been in the commissioning stage since the beginning of 1989. It aims the beam acceleration up to 1.1 GeV for proton and to 370 MeV/u for heavy ions of q/A=0.5, corresponding to the maximum magnetic rigidity of 6.1 T.m. An electron cooling device and a slow extraction channel are prepared for various beam experiments. In the present paper, the status of TARN II is described as well as the results of preliminary beam experiments.

Introduction

TARN II is an experimental facility for accelerator, atomic, and nuclear physics with an electron cooler equipment as well as the functions of beam acceleration and slow extraction.[1] 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, just 17-times that of the extraction orbit of the injector SF cyclotron. It has 6 long straight sections of 4.2 m length each, which are used for the beam injection system, an RF cavity, an electron cooling device, and a slow beam extraction system. It takes 3.5 sec for the power supply to excite the whole magnet system to the full excitation. The flat top duration of magnetic field is variable and sufficiently long for the beam cooling and extraction. The peak electric power for the magnet excitation is 2000 kVA and related power consumption is 1 MW. 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, corresponding to the maximum electron energy of 120 keV. It consists of an electron gun, an interaction region of 1.5 m in length, collector and electron guiding coils.[2]

At present, all the 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 experiments of beam injection and accumulation have been performed for several days per month as well as the fundamental studies on the effects of electron beam on circulating ion beams. In September 1989, the first e-cool experiments was performed successfully with use of 20 MeV proton beam. Further experiments of beam acceleration and cooling are scheduled in the following several monthes.

Magnet system

The focusing structure of the magnet system is based on an 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. (Fig. 1) The whole circumference is composed of six unit cells. For the synchrotron acceleration mode, these cells are excited identically

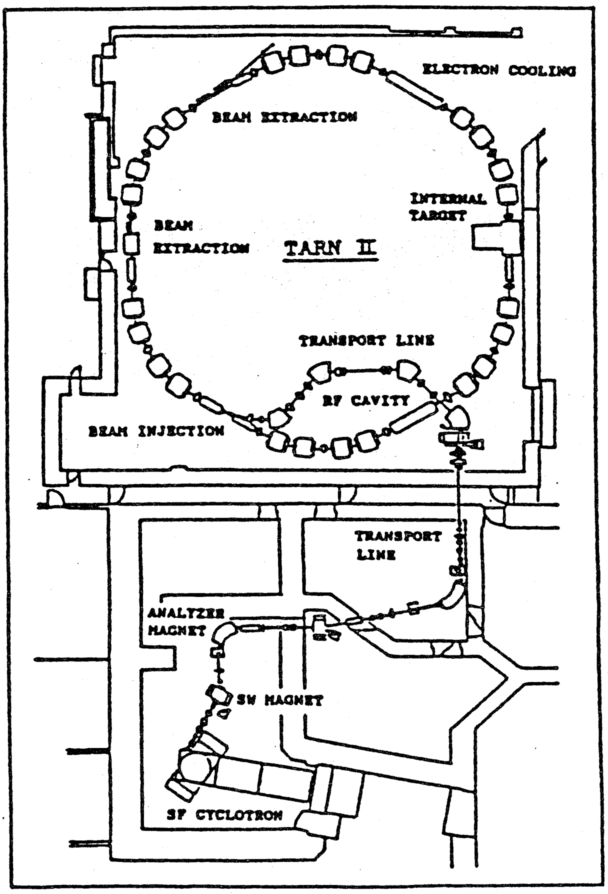

Fig. 1 Layout of TARN II

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 mm^2
Vacuum pressure		10^{-11} Torr

approximately 40μ sec which corresponds to about 20-30 times of the revolution period of the beam in the ring. The frequency of RF field was set to be the value corresponding to the harmonic number 2 of the beam circulation. (1.587 MHz for proton 20 MeV). In Fig. 2, the signals of plsed arc in the cyclotron, discharged currents of kicker magnet and those of two bump magnets. From the beam signal of the electrostatic monitor, the gain of intensity of the circulating beam was increased by about 14 turns, which realizes well the expected value of the simulation. The RF frequency and voltage were so adjusted as to get the maximum capture efficiency.

The lifetime of the beam was measured by the decay constant of the signal from one of the electrostatic monitors (Fig. 3). The e-folding lifetime was found to be 12 sec. It was determined by the scattering with the residual gas. This lifetime is roughly in agreement with the calculated result on the condition that the average vacuum pressure in the ring was about 2 x10^{-9} Torr and the α beam energy was 7 MeV/u. In these early experiments, the vacuum chambers were not yet baked out.

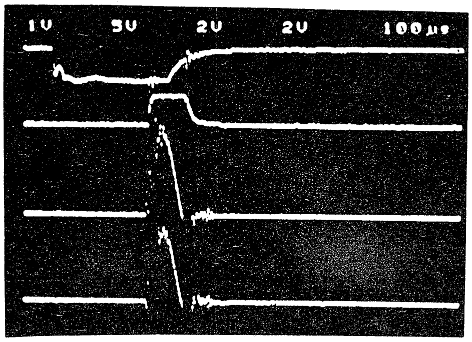

Fig. 2 Pulse shapes of cyclotron arc, magnetic fields of kicker magnet and two bump magnets. (From top to bottom)

The electron cooling experiment was performed for 20 MeV proton beam which was injected into the ring by multiturn injection method. Number of injected particles was about 10^7. After the adjustment of correction magnets which compensate the effects due to the solenoid and toroidal magnetic fields of electron equipments, we observed the cooling effect and the momentum spread of stored proton beams was improved from the initial value of 2x10^{-3} to the final value of 2x10^{-4} with the e-folding cooling time of 1.4 sec. Typical time evolution of momentum spread, equivallently the spread of revolution freaquency, was given in Fig. 4. Machine parameters relavant to the electron cooling is given in Table 3 and the details of cooling experiments are presented in the other paper in this symposium.[9]

Table 3

Machine parameters relavant to the electron cooling

Proton beam energy	20.26	MeV
Electron beam energy	11.04	KeV
Electron current	0.3	A
Initial momentum spread, $\Delta p/p$	2x10^{-3}	
Final momentum spread	2x10^{-4}	
RF frequency	1.578	MHz
Harmonic number	2	
Horizontal β at cooler section	10.2	m
Vertical β at cooler section	3.7	m
Momentum dispersion at cooler section	4.7	m
Horizontal betatron tune	1.71	
Vertical betatron tune	1.81	

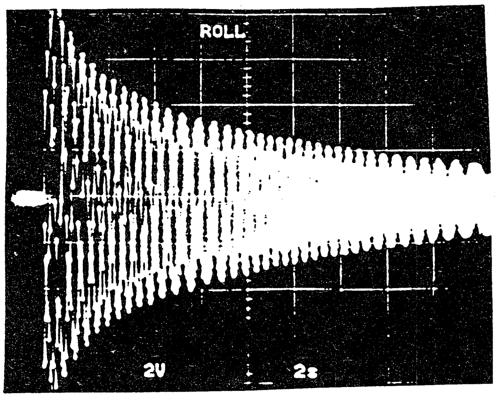

Fig. 3 Beam signals from the electrostatic monitor. Horizontal scale is 2 sec/div.

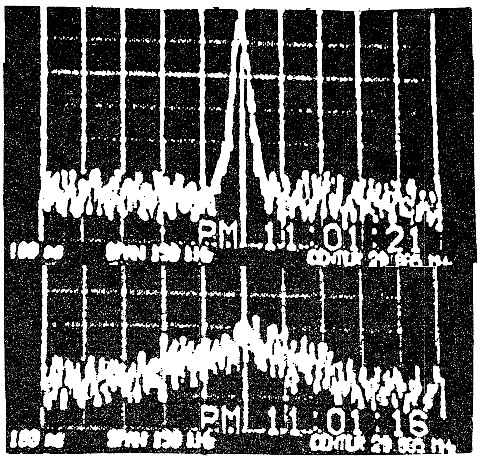

Fig. 4 Time evolution of frequency spectrum of a bunched proton beam after injection with cooling. Horizontal scale; 15 kHz/div, vertical ; 5dB/div, and central frequency ; 29.985 MHz.

References

1 T. Katayama, "Heavy Ion Accelerator and Cooler -TARN2-", Proc. 11th Int. Conf. on Cyclotrons and Their Applications (Ionics, Tokyo, 1986), pp.128-132.

2 T. Tanabe, et al., "Electron Cooler at INS" Proc. Particle Accelerator Conf., March 1989, Chicago, to be published.

3 A. Noda, "Heavy Ion Synchrotoron-Cooler Ring, TARN II", Proc. IEEE Particle Accelerator Conf., 1987, pp.846-847.

4 S. Watanabe et al., "Computer Control of TARN2 Main Ring Power Supply" To this symposium.

5 K. Chida, et al., "Vacuum System of TARN II," To this symposium

6 K. Sato, et al., "RF Acceleration System for TARN II", Proc. 11th Int. Conf. on Cyclotrons and their Applications (Ionics, Tokyo, 1986), pp.333-336.

7 F. Soga, et al., "Design of the Slow Extraction System at TARN II,", Proc. 6th Symp. on Accelerator Science and Technology (Ionics, 1987,Tokyo),p.268-270.

8 A. Noda et al., "Slow Beam Extraction from TARN2" To this symposium

9 T. Tanabe et al.,"Initial Electron Cooling Studies in the TARN2", To this symposium

and the dispersion function and the maximum β_x-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_x-value becomes large and the acceptance is reduced to 140π mm.mrad.[3]

The excitation of current for the magnets are per formd with four power supplies, one for the dipole magnets and three for the quadrupole magnets. The ramp shape of the dipole field B is a trapezoid wave form with a repetition rate of 0.1 Hz and the rising period is 3.5 sec. The dB/dt signal is used for the pattern production of RF acceleration frequency. The currents of three power supplies of Q magnets are tracked with the bending magnet current within the tracking error less than $1x10^{-4}$ with use of the self learning procedure in the control computer system.[4]

Vacuum system

It is required for the vacuum condition of better than 10^{-10} for the heavy ion accumulation and acceleration and then the vacuum chamber and other elements are made of organic free materials. The ramping rate of magnetic field is so low as 0.4 T/sec and then the vacuum chambers at dipole and quadrupole magnets are made of SUS 316L with thickness of 4 mm. They are bakable up to 350 °C by heating with current flowing directly through them. Between each pair of dipole magnets, 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 in order to pump the ring differentially. Totally, 7 titanium sublimation pumps (1500 l/s), 5 sputter ion pumps (800 l/s), 3 sputter ion pumps (400 l/s), and 3 turbo-molecular pumps (500 l/s) are used for the evacuation. Presently, the average vacuum pressure in the ring is several times 10^{-9} Torr and the goal of 10^{-11} Torr will be obtained after the baking of chambers.[5]

RF system

The lowest injection energy has been set to be 2.58 MeV/u for $^{20}Ne^{4+}$ among the various ions from the SF cyclotron, corresponding to the revolution frequency of 0.307 MHz. At the top energy of 1100 MeV for protons, the revolution frequency is 3.5 MHz, thus the ratio of the lowest to highest frequencies is thirteen. The harmonic number was chosen to be 2 and the designed acceleration frequency is 0.6 MHz to 7.0 MHz. An acceleration voltage of 2 kV is enough for the beam with 0.5 % momentum spread within the acceleration period of 3.5 sec.

An rf cavity, a single-gap, ferrite-loaded, two quarter-wave coaxial resonators, has been constructed. It covers the frequency range from 0.61 to 8.0 MHz by changing the ferrite bias current from 0 to 770 A. A power amplifier with a maximum output power of 5 kW can produce 2 kV of accelerating voltage over the gap throughout the whole frequency range.[6]

The low level RF electronics system is composed of a voltage controlled oscillator(VCO) and several feedback loops. Three memory modules store the functional forms of frequency, voltage and bias current to be produced as a function of the field strength. At every increment 1 Gauss of the magnetic field, measured at the 25th dipole magnet for field monitoring, the data are read from memories and converted into analog voltages through DAC's. They are fed into a voltage controlled oscillator, amplitude modulator and bias current power supply, respectively. The error of bias current or equivallently the degree of detuning of cavity is detected as the phase difference between the RF signals at the grid and the plate of final power tube. It is used for the correction of resonance frequency of cavity via a hardware feedback loops(AFC). In addition, the signals of beam position (Δ R)and of the phase error ($\Delta \phi$) between beam bunch and acceleration RF field, are fed back to the voltage controlled oscillator. The output rf signal of this oscillator is fed to driver and power amplifiers.

On the other hand , at the injection period the VCO is phase locked with the RF signal from a frequency synthesizer. The frequency and voltage at this period are finely adjusted manually to get the maximum capture efficiency.

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 emmittane (60π mm.mrad). To respond these requirements, high-efficient extraction method was proposed[7] with use of rather complicated ajustment of the currents of dipole magnet and quadrupole magnet. In viewing this scheme as a final goal, as a first trial of the extraction, a simple extraction method has been in progress where one 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. 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 non-linear sextupole field at the injection energy.[8] An electric septum, 70 kV/cm and 1.0 m long, is located in the second straight section and the first septum magnet, 5 kG in magnetic field strength and 1.0 m long, is at the third straight section.

The emmitance of the extracted beam is calculated at 5π mm.mrad and the extraction efficiency is around 90 %. Main parameters of slow extraction are given in Table 2.

Table 2

Parameters of slow extraction system

Ion species	p, α , ∼ Ne
Beam energy	150∼370 MeV/u
Extraction scheme	1/3 resonance
Operating point	(1.6667, 1.80)
Septum position	75 mm outside from central orbit
Beam emmitance	Circulating beam < 50 π mm.mrad Exracted beam 5π mm.mrad
Momentum spread	±0.2%

Beam experiments

At the beginning of 1989, the first experiment of multiturn injection was performed with the pulsed beam of 28 MeV α particles. At the exit of the SF Cyclotron, the beam emmitance was measured at 15 π mm.mrad (horizontal) and 20 π mm.mrad (vertical), respectively and momentum spread was 0.2%. The one third of the beam was transported from the exit of cyclotron to the injection point of the TARNII. Since then, several times, multiturn injection were tried by using either 28 MeV α or 20 MeV proton beams. Usually the pulse width and the repetition rate at the ion source were 3 msec and 30 Hz, respectively. The beam was injected into the ring with the excitation of two bump magnets. The decay time of bump fields were set to