STATUS OF HEAVY ION COOLER SYNCHROTRON TARN II

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ABSTRACT

A cooler/synchrotron TARN II has been under construction for these three years. Recently, it has come to a stage that beam injection and acceleration experiments started and the electron cooling device has been successfully off-line tested. The status of the TARN II ring is described including some of the recent results of beam experiments.

1. INTRODUCTION

The TARN II is a heavy-ion cooling ring with functions of synchrotron acceleration for accelerator studies and for atomic and nuclear physics. It has been under constructtion since 1986, when the old TARN II ring was disassembled.1) This ring is essentially an extension of the old TARN2) both as a concept and as an apparatus.

The primary aim of the TARN II ring is, therefore, to push the accelerator technologies achieved in the old TARN ring further. After the successful experiments of storage of protons and Carbon ions at 7 MeV/u and stochastic cooling of protons and α particles at the this energy,3) the upgrading plans of the TARN for electron cooling were put forward and the TARN II started. Much emphasis is placed upon the electron cooling of heavy ions.

The construction has made progress steadily and almost all components necessary for accumulation, acceleration, storage and electron cooling of lighter heavy ions are prepared. Initial beam injection was successful and further experiments are under way. The electron beam has been tested successfully at an off-line position up to 70 kV and 2 A of electron beam. In this report, main features of this ring are summarized together with preliminary results of recent experiments.

2. INJECTION FROM SF CYCLOTRON

The injector of the TARN 2 ring is a sector-focusing cyclotron, SF cyclotron, with an K number equal to 68.4) It is routinely used for experiments of nuclear physics and other applications. The extraction mean radius is 72.8 cm and operation frequency is from 7.5 MHz to 22.5 MHz. It has been using an internal PIG source for light and heavy ions. An ECR heavy ion source has been developed for this cyclotron and a new vertical injection line is being prepared for this ion source.5)

The first half part of the beam transport

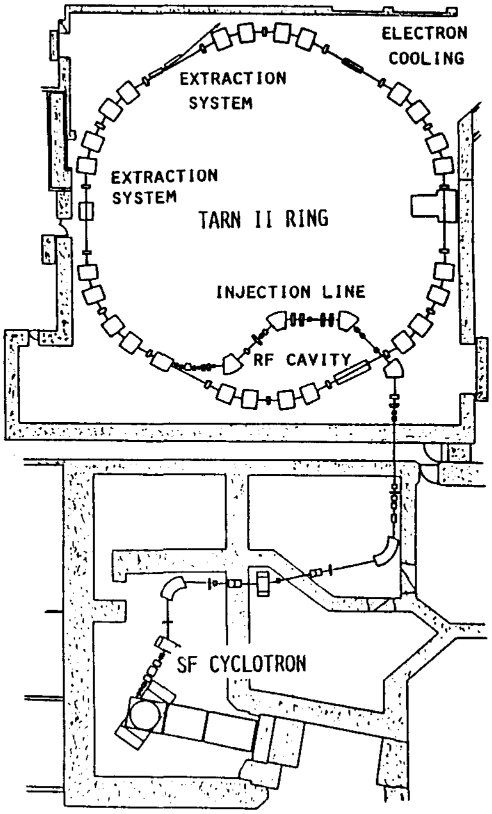

Fig. 1 Plan view of SF cyclotron and TARN II

line from the SF cyclotron to the old TARN ring[6] is not changed for the new ring. The second half part, nearer to the ring, has been newly constructed for the new ring. It comprises of two beam analyzers, six bending magnets, a kicker magnet and two stages of electrostatic inflector channels together with 20 quadrupole magnets. It has been designed to accept the beams from the SF cyclotron with emittance of about 20π mm.mrad both in the horizontal and vertical directions and with a momentum spread of 0.5 %.

In front of the first beam analyzing magnet, a stripper foil is placed to strip the remaining electrons off to make the fully stripped ions. The electric inflector channels are two curved plates with 8 mm width. For multi-turn injection, two bump magnets are installed in the ring for making the closed orbit displacement by about 8 cm at its peak at the injection point.

Assuming the designed orbit parameters at the injection point and the two bump magnets presently used, calculations for multiturn injection show that about 15 to 20 times of increase of the injected beam intesity is possible by filling the transverse phase space with about 50 turns of injection.[7]

Typical ions from the SF cyclotron which can be injected into the ring with enough intensity for the beam monitor to control the beam, more than about 10^6 circulating particles, are listed in Table 1. It is assumed that the overall efficiency coming from beam transport, stripping and injection is 20 % and the effective number of the multi-turn injection is 20.

Table 1

Typical ion species and number of circulating particles expected for TARN II

	energy from SF cyclotron (MeV/u)	intensity (μA)	numbers of circulating ions (particles/pulse)
proton	20	30	7×10^8
He	10	30	4×10^8
C	7.7	10	4×10^8
N	8.8	10	3×10^7
O	6.6	5	2×10^8
Ne	6.2	5	1×10^7

3. DESCRIPTION OF TARN II RING

3.1 Magnet

The ring is regular hexagonal in shape with an average diameter of 24.8 m. The circumference of the ring is 77.76 m, 17 times of that of the outermost orbit of the injector cyclotron. The maximum magnetic rigidity of the dipole magnets is 6.1 T.m, which is limited by the capability of the power supplies and electric power capacity of the institute. This corresponds to 1.1 GeV for protons and 370 MeV/u for ions with q/A = 1/2. The main parameters are shown in Table 2.

Table 2

Main Parameters of the TARN II Ring

max. magnetic rigidity	6.1 T.m
max. beam energy proton	1.1 GeV
ions with q/A=0.5	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 magnetic excitation	3.5 sec to full
max. repetition rate	0.1 Hz
max. field of dipole magnets	15.0 kG
max. field 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	50×200 mm^2
vacuum pressure	10^{-11} Torr

The ring consists of 24 dipole and 18 quadrupole magnets. The lattice is based on a simple FODO structure with six-fold symmetry. The ring can be operated in two different modes: one is for accerelation with superperiodicity 6 and the other is for cooling with superperiodicity 3. The former affords a wider acceptance for acceleration and the latter, three dispersion-free long straight sections and three dispersive sections for electron cooling and internal target, respectively. They can be transferred each other, keeping the operating point in the tune diagram unchanged.

Six long straight sections are made by inserting drift space of 4.2 m length between horizontally focusing magnets at every unit cell. One of them is used for beam injection, one for acceleration cavity, one for electron cooling, two for beam extraction and the remaining is left for future utility.

The magnetic field of the bending and quadrupole magnets was measured and found that the former can be used from 1.25 kG up to 15 kG and the latter, from 2.6 kG/m to 70 kG/cm without serious distortion of the closed orbit. They all have been set into their position with an overall accuracy of ± 300 μm by aligning them with Invar wires calibrated by a laser interferometer. About 1/3 of the error is estimated to be due to daily and long-term deformation of the building and the magnet base.[8]

The magnets are excited by four power supplies, one for the bending and the other three for the quadrupole magnets. The excitation wave form is trapezoidal in shape, allowing long and stable flat-top part. The rising rate is constant and it takes 3.5 sec from 200 A (minimum) to 2500 A (maximum) with maximum repetition rate of 0.1 Hz. A computer-cotrolled tracking system is being prepared with a learnig function for error correction.$^{9)}$

3.2 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 accerelation period of 3.5 sec.

An rf cavity, a single-gap, ferrite-loaded, quarter-wave coaxial type, has been constructed.$^{10)}$ 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 an maximum output power of 5 kW can produce 2 kV of accelerating voltage over the gap throughout the whole frequency range.

Three memory modules store the functional form of the frequency, voltage and bias current to be produced as a function of the field strength. At every increment of the magnetic field, measured at the 25th dipole magnet for field monitoring, the data are read from the memory and converted into analog voltages through DAC's, which are fed into a voltage controlled oscillator, amplitude modulator and bias current power supply, respectively. The error of bias current and frequency are corrected by hardware feedback loops. In addition, position and phase error signals are picked up from the beam monitor and fed back to the voltage controlled oscillator. The output rf singnal of this oscillator is fed to the amplifier.

At the injection, however, the signal is fed from a frequency synthesizer and frequency and voltage are finely adjusted manually to get maximum capture efficiency.

3.3 Vacuum System

The vaccum chambers are mainly made of 316L stainless steel and pure alumina ceramics. They are bakable up to 350 ℃ 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. Presently, since pumps are working only partially and no baking has been made, the vacuum is around 10^{-8} Torr. The goal is 10^{-11} Torr after every effort.$^{11)}$

3.4 Extraction System

A slow beam extraction system with high efficiency has been designed which uses the third integer resonance.$^{12)}$ Since the energy of the extracted beam are required to vary over wide energy range from 150 MeV/u to 1100 MeV/u, the emittance of the circulating beam on which the extraction system has to work is rather large, 60π mm.mrad. To meet this requirement, this design uses complicated adjustment of the current through the dipole magnets.

Setting this design as a final goal, a simpler scheme is being prepared as a first step. A sextupole magnet is used to excite the resonance and the closed orbit is displaced by three bump fields. Computer simulation shows that it works for the circulating beam with emittance of 60π mm.mrad and that the emittance and momentum spread of the extracted beam are 5π mm.mrad and 0.2 %, respectively.

4 ELECTRON COOLING DEVICE

An electron cooling device has been manufactured, which is designed to cool the ion beam with energy up to 200 MeV/u in the ring. The main parameters are shown in Table 3.

It consists of an electron gun, a 1.5-m long interaction region, an electron collector and electron-guiding coils. The gun can supply an electron beam with maximum current of 10 A with a diameter of 5 cm. The maximum electron kinetic energy is 120 kV. The collector can stop the electrons at 5 keV.

The vacuum test has shown that after baking at about 250 ℃ the vacuum pressure reached to 10^{-11} Torr without the electron beam. The off-line electron beam test has started. The system has been gradually aged and the stable electron beam has been obtained up to 70 kV with intensity of 2 A.$^{13)}$

Table 3

Parameters of electron cooling device

max. working energy	ion	200 MeV/u
	electron	120 keV
object ions		H^+ - ^{20}Ne^{10+}
length of interaction region		1.5 m
max. current density		0.5 A/cm^2
cathode diameter		5.0 cm
max. electron current		10 A
max. solenoid field		1.2 kG

5 FIRST BEAM EXPERIMENTS

The test started in the fall of 1988. Since then, a few of the SF-cyclotron beam times were allocated for the TARN II experimtents. The 28 MeV α particles were chosen for these initial experiments.

The emittance of the extracted beam was measured to be 15π mm.mrad (horizontal) and 20π mm.mrad (vertical) and the momentum spread was 0.2 %. These values differed a little time to time. The average beam current was 10 to 20 μA for the dc operation of the ion source and up to about 10 μA for pusle operation of the ion source. The pulse width and repetion rate in the case of pulse operation were 1 msec and 30 Hz, respectively.

Generally, 30 % of the extracted beam was transported to the the injection point of the ring through the transport line of about 55 m long. At the inflector channel, the beam was focussed and the measured transmission of the inflector was found to be better than 80 %.

The time constant of the decay of the bump magnets was adjusted to be 40 μ sec corresponding to 20 times the revolution time of the 28 MeV α particles. The injected beam was adiabatically captured by the rf voltage after 500 μ sec after injection. The rf frequency and voltage were so adjusted as to get maximum capture efficiency.

The lifetime of the beam was measured by the decay constant of the signal from one of the electrostatic monitors (Fig. 2). The e-folding lifetime was found to be 3.5 sec. It is mainly determined by the scattering with the residual gas. This lifetime is reasonable, because the average vacuum pressure in the ring was about 2 × 10^{-8} Torr and the beam energy was rather low, 7 MeV/u. In these early experiments, the vacuum chambers were not yet baked out and three turbo-molecular pumps and six ion pumps were working. In the next coming beam time the pressure is to be improved up to 10^{-10} Torr and the lifetime is expected to be greatly improved.

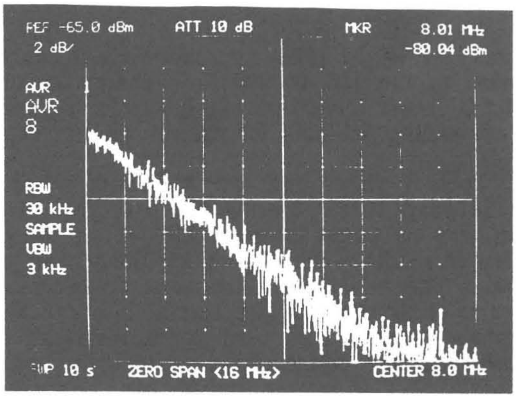

Fig. 2 Beam signal from an electrostatic monitor showing the decay of the beam. The scales are 1 sec/div (horizontal) and 2 db/div (vertical).

The amplitude of the signal from the monitor was calibrated by measureing the one passage of the beam and the increase of the amplitude of the signal was measured when the beam is circulating. The number of the circulating particles thus measured is 4 × 10^8 and the number of multiturn injection was about 6. This value is still lower by a factor of about 3 than the calculated one by the computer simulation. The injection orbit was not yet optimized in this early stage. Improvement of the injection orbit will be made by means of six correction coils on the six of of 24 bending magnets.

In the nearest future, accerelation of the α particle is to be tried, for which every equipments are ready. Before summer, first trial of electron cooling is planned.

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