# TARN II PROJECT

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## ABSTRACT

On the basis of the achievement of the accelerator studies at present TARN, it is decided to construct the new ring TARN II which will be operated as an accumulator, accelerator and stretcher. It has the maximum magnetic rigidity of 7 T·m corresponding to the proton energy 1.3 GeV and the ring diameter is around 23 m. Light and heavy ions from the SF cyclotron will be injected and accelerated to the working energy where the ring will be operated as a desired mode, for example a cooler ring mode. At the cooler ring operation, the strong cooling devices such as stochastic and electron beam coolings will work together with the internal gas jet target for the precise nuclear experiments. TARN II is currently under the construction with the schedule of completion in 1986. In this paper general features of the project are presented.

## INTRODUCTION

TARN (Test Accumulation Ring for Numatron) is a storage ring, built for the development of accelerator technique of beam accumulation and stochastic cooling with a view of future application in a scheme of high energy heavy ion accelerator complex, Numatron. The idea[1] of beam accumulation both in the horizontal betatron and in the longitudinal phase spaces as many ions as possible and recently verified.[2] The momentum cooling with the stochastic system was also successfully tested.[3,4] For the accumulation experiments twenty turn beam were injected in the betatron phase space of 87 πmm·mrad with a multiturn injection method and 15 pulses are RF stacked in the momentum space $\Delta p/p$ of 2.2 %. Overall stacking number was then attained at around 300 turns. The stochastic cooling experiment was performed on the RF stacked beam to decrease its momentum spread. With the feedback system of active gain 107 dB and band width 100 MHz, the initial momentum spread 1.4 % was cooled down to 0.2 % within 20 seconds for the 7 MeV proton beam of $7 \times 10^7$.

On the basis of these successful achievements of accelerator studies, we have decided to construct the improved TARN, TARN II which will accumulate, accelerate and stretch the ion beam from the cyclotron and/or the planned injector linac. The maximum $B\rho$ of TARN II is 7 T·m and the corresponding proton beam energy is 1.3 GeV and the energy of full stripped ions such as $C^{6+}$ is 450 MeV/u. Cooling devices of both the stochastic and electron beam will cool the horizontal and vertical emittances and momentum spread of the stored beam. With these cooling devices it is expected to obtain a quasi-monochromatic ion beams of the momentum spread better than $1 \times 10^{-4}$.

In the meanwhile, inspired by the success of the beam accumulation and cooling technique at CERN and INS, several laboratories[5,6,7] are enthusiastically planning and discussing on the application of cooler ring to nuclear physics. In the cooler ring, the stored beam continuously circulate through a thin internal target, and the beam approaches an equilibrium between heating by the target and cooling with stochastic feedback and/or cold electron beam. Although the product of target thickness and beam current is not higher than the conventional one-pass experiments with the extracted beam, the luminosity can be increased to around $10^{31}$ with a thin target of $10^{14}$ atms/cm$^2$ due to the advantage of the revolution in the ring. The beam is not being dumped during the measurement and then the background conditions will be much improved over a conventional one pass experiment. With use of the fast cooling devices, the equilibrium emittances and momentum spread can be maintained as small even when the internal target is inserted in the ring orbit. In addition to the well energy resolution and good angular resolution, the ion energy can be also changed in small steps such as 10 KeV or so with use of the stochastic acceleration technique, which should be useful for the studies of threshold or resonance effects in nuclear reactions.

TARN II is currently under the construction with schedule of the completion in 1986. The goals of the project is firstly to boost up the beam energy to several hundreds MeV/u, secondly to cool down the beam temperature in three phase spaces and thirdly to perform the nuclear experiments with an internal target.

## INJECTOR AND AVAILABLE IONS

In the present scheme, the injector of TARN II will be a SF cyclotron with the K number of 67. On the other hand we are now planning to construct the heavy ion linear accelerator with the output energy of around 5 MeV/u, probably being able to accelerate the heavy ions up to Xe beams. This linac is now, however, the stage of discussion and then the injector of TARN II is the cyclotron at the first stage and the linac will take the place of the cyclotron in future. The SF cyclotron can accelerate various kinds of ions from the light ions of p, α, to heavy ions $Fe^{8+}$. However due to the restriction of internal ion source, the charge state of heavy ions is low and the output energy is correspondingly quite low. Among these heavy ions, $Ne^{4+}$ beam will be the heaviest ions which has the reasonable current ∿ 1 μA and the energy 2.6 MeV/u which is adequate for the acceleration in TARN II. In Table 1, the heavier ions are listed with the available intensities and energies from the cyclotron.

Table 1 Heavy Ion Beam from SF Cyclotron

| Charge State | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| $^{6}Li$ | 7.6<br>4.5 | 17.0<br>1.0 | | | | |
| $^{7}Li$ | 5.6<br>1.0 | 12.5<br>0.3 | | | | |
| $^{11}B$ | 2.2 | 5.1<br>3.0 | 9.0 | | | |
| $^{12}C$ | | 4.3 | 7.6<br>5.1 | 11.8<br>0.025 | | |
| $^{14}N$ | | 3.1<br>10.0 | 5.6<br>5.5 | 8.7<br>3.0 | 12.5<br>0.006 | |
| $^{16}O$ | | | 4.3 | 6.6<br>1.5 | 9.6<br>0.07 | 13.0 |
| $^{20}Ne$ | | | 2.7<br>1.7 | 4.3 | 6.1<br>0.1 | 8.3<br>0.01 |

Upper Kinetic Energy K = 68 (MeV/u)
Lower Extracted Beam Intensity (eμA)

TARN II will be installed in the new accelerator hall which is made by clearing up the Old Experimental Hall of the FM cyclotron and present TARN room. (Fig.1) Ions from the SF cyclotron are transported through the beam line presently used for TARN, and at the stripper section located just prior to the analyzer magnet in the line, the orbital electrons of partially stripped ions are completely taken off. After that ions are injected in TARN II with the multiturn injection and/or the RF stacking method. The injection energy is different from each other for various ions as is given in Table 1 for heavier ions whereas the proton injection energy will be

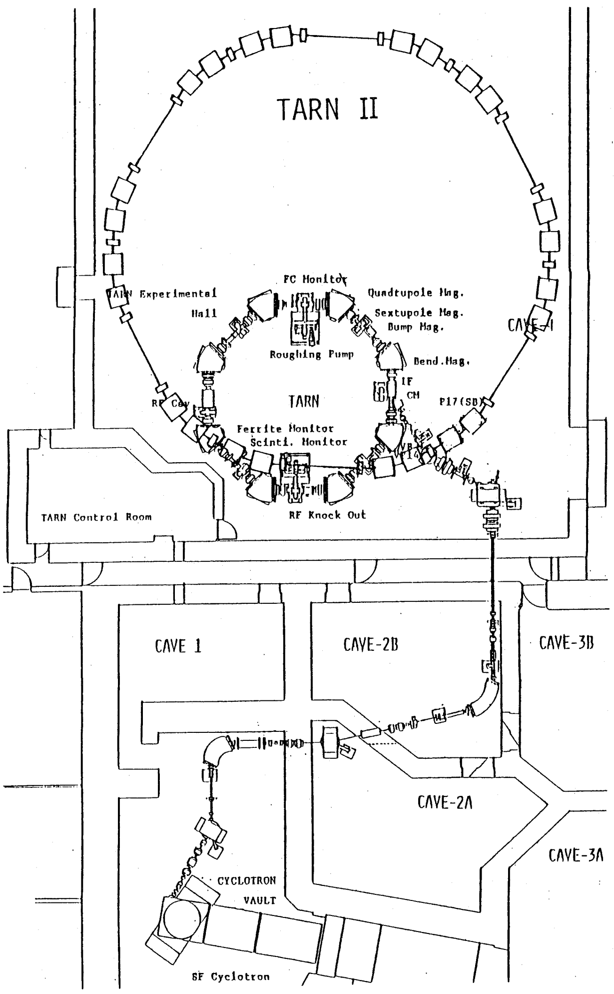


Fig.1 Layout of Present TARN and TARN II

20 MeV. During the process of passing through the thin carbon foil $\sim$ 50 $\mu g/cm^2$ at the stripper section, beam qualities will be degrated, for example the emittance will be grown up due to the multiple scattering and the energy spread will be enlarged with the straggling effects. As a most serious case, $Ne^{4+}$ beam of 2.6 MeV/u is examined here which shows the emittance 20 $\pi$mm·mrad of the beam from the cyclotron will be increased up to 35 $\pi$mm·mrad and the energy straggling will be around $1 \times 10^{-3}$. The fraction of full stripped ions is estimated at one third.

The cyclotron is essentially the CW machine, not having the high peak current and does not fit to the injection of the pulsed operating accelerator such as synchrotron. For the present TARN, the peak current at the injection point is around 1 p$\mu$A (p, $\alpha$) and 0.1 p$\mu$A (heavier ions) after passing through the beam transport line with magnetic analyzer system. The momentum spread of the injected beam is around ± 0.1 % which comes from the narrow phase spread ± 2 degree in the RF acceleration field of the AVF cyclotron. The horizontal and vertical emittances are 10 $\pi$mm·mrad for p, d, $\alpha$ and 35 $\pi$mm·mrad for heavier ions. As the acceptance of TARN II is designed at 400 $\pi$mm·mrad and the dilution factor during the process of multiturn injection is assumed at 2.5, being experimentally verified at the present TARN, and the expected beam intensities are around $1 \times 10^8$ for p, $\alpha$, d and $1 \times 10^6$ for heavy ions. However if one uses both the horizontal betatron and longitudinal phase spaces, the expected intensity will be increased up by the order of two. This is mainly due to the fact that the AVF cyclotron beam has a quite small longitudinal phase spaces $\varepsilon_\ell = \Delta\phi \cdot \Delta T/T$, around $5 \times 10^{-4}$ (rad).

Beam life time at the injection energy is mainly determined, for heavy ions by the charge capturing process of full stripped ions through the collisions with residual gases and for the light ions such as proton and $\alpha$ by the Rutherford scattering. Assuming the vacuum pressure in the ring as $1 \times 10^{-10}$ Torr, the beam life is estimated as follows: p (20 MeV); 3300 sec, $C^{6+}$ (7.6 MeV/u); 760 sec and $Ne^{10+}$ (2.7 MeV/u); 12 sec. From the arguments on this beam life at the injection energy, it is expected that there is enough time for the beam manipulation such as RF stacking or fast stochastic cooling even at the flat base, injection period.

## GENERAL DESCRIPTION OF THE RING

### Modes of Operation

The ring will be used in three modes;

1) normal synchrotron operation,
2) long spill operation, stretcher mode, and
3) cooler ring mode.

In the synchrotron mode, the repetition cycle is 0.5 Hz with the acceleration period of 0.75 sec, the flat-top of 0.5 sec and the falling period of 0.75 sec. This repetition rate is determined mainly due to the available electric power at the present INS electric station. In the stretcher mode, the acceleration period will be around 10 sec, whereas the flat-top will be long enough, say 1 hour for 500 MeV protons, which should be a good compromise between the beam life and the ultra-slow ejection method such as stochastic extraction. At the cooler ring mode, the operation scheme will be the same for stretcher mode while the strong beam cooling devices will be operated as well as the internal gas jet target.

### Lattice

A set of preliminary lattice parameters for stretcher and cooler modes is given in Table 2, and the lattice functions are shown in Fig.2. The circumference 69.908 m is the maximum size of a ring that fits into the new accelerator hall. A symmetric three-period lattice with the six long straight sections of 4 m long each, was adopted. Hence there are three dispersion-free straight sections and three large dispersion sections, of which the feature is adequate for the beam cooling and the internal target experiments. In the dispersion-free straight sections, an electron cooling device, stochastic cooling kickers and an RF accelerating cavity will be installed, while the large dispersion sections are prepared for stochastic cooling pickups, internal target system and the electric inflector for the beam injection.

Table 2 Specification of TARN II

| | | |
|---|---|---|
| Maximum Beam Energy | proton | 1300 MeV |
| | ions with $\varepsilon = 1/2$ | 450 MeV/u |
| Circumference | | 69.908 m |
| Average Radius | | 11.650 m |
| Radius of Curvature | | 3.820 m |
| Focusing Structure | | FBDBFO |
| Superperiodicity | | 6 |
| " for Cooler Ring Mode | | 3 |
| Betatron Tune Value | | around 1.75 |
| " for Cooler Ring Mode | | $\nu_H$ around 2.25 |
| Transition $\gamma$ | | 1.87 |
| Repetition Rate for Synchrotron Mode | | 1/2 Hz |
| Maximum Field of Dipole Magnets | | 18 kG |
| Deflection Angle of Dipole Magnets | | 15° |
| Maximum Gradient of Quadrupole Magnets | | 70 kG/m |
| Revolution Frequency | | 0.38 - 3.75 MHz |
| Acceleration Frequency | | 0.76 - 7.50 MHz |
| Harmonic Number | | 2 |
| Maximum RF Voltage | | 6 kV |
| Vacuum Pressure | | better than $10^{-10}$ Torr |

### Magnets

In the renovation process of TARN, the whole dipole

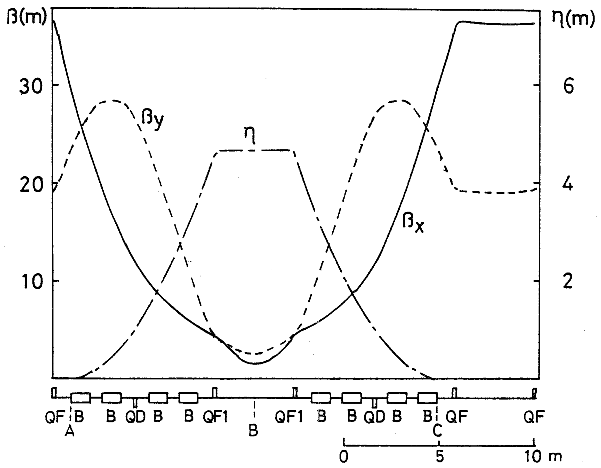


Fig.2 Orbital Functions at Cooler Ring Mode

magnets are rebuilt, while the quadrupole magnets being used in the present TARN will be again used for TARN II. The magnetic structure of the new ring is made up of 24 dipole magnets and 18 quadrupole magnets. Each dipole magnet is an H type structure with the straight core length of 1 m. The edge shape at the end of yoke is approximately Rogowsky curve, cutting the yoke with four steps. The designed field region is 200 mm in width and 60 mm in vertical directions. So as to realize the large good field region for the wide excitation range up to 18 kG, the side pole edges are shaped with B constant curve. Also the small shims are attached to suppress the falling down of the magnetic field at pole ends at the high field of saturated condition.[9]

Acceleration

An RF system will accelerate the ion from the injection energy to the desired 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 ∿ 500 MeV/u, the revolution frequency is 3 MHz and the RF frequency ratio of the initial and final stages is ten. The harmonic number is chosen as two and the designed acceleration frequency changes from 0.6 MHz to 6 MHz. An RF voltage of 6 KV seems adequate for the acceleration of the beam with the momentum spread of ± 0.5 % within the acceleration period of 0.75 sec. This RF voltage is produced using a cavity loaded with ferrite 2.5 m long.[10,11]

Vacuum

The residual gas has several effects on beams circulating in TARN II, namely 1) the charge capturing process of full stripped heavy ions leading to beam loss, 2) multiple Coulomb scattering of light ions determines the beam life in the ring, 3) contribution to background when the jet target experiments are performed. The estimation of the beam life at the injection energy shows that the vacuum pressure of ∿ $10^{-11}$ Torr should be achieved. In the present TARN, an all metal vacuum system bakable at 200°C are used with eight sputter ion pumps and eight titanium getter pumps. The normal operating vacuum pressure better than $1 \times 10^{-10}$ Torr is achieved with storing the beam and the similar system will be used also for TARN II.

Slow Ejection

In the synchrotron mode operation, the beam will be extracted with use of one-third resonance at the flat-top period of ∿ 0.5 second. The extraction system consists of following elements. 1) four bumps magnets for the closed orbit distortion, 2) four sextupole magnets as a chromaticity adjustment and a resonance excitor, 3) an electrostatic and three magnetic septum in the extraction channel. Comparing with the several extraction resonances, one-third resonance is chosen as it can give the extraction efficiency around 90 % and the small beam emittance. When the ring is operated as stretcher mode, the spill time would be order of 100 seconds which requires the beam being far off the linear resonances to avoid the sudden beam loss. To perform this ultra-slow ejection, the stochastic extraction system practised at CERN, LEAR, will be used with the combination of stochastic cooling system and normal extraction equipments.[12]

## BEAM COOLING AND INTERNAL TARGET

Both the stochastic and electron beam coolings will be used to obtain the high quality beam. For the stochastic cooling, there will be used two systems, one being the precooling and the other the high energy cooling. With a precooling system, the momentum spread of the injected beam from the cyclotron and/or the linac will be improved. Especially when the RF stacking is employed as an injection method, this precooling is indispensable to maintain the acceleration RF voltage as reasonably small as possible. The RF stacked beam will have the momentum spread of ± 1 % and it should be decreased to ± 0.2 % to accelerate the beam within the designed RF voltage 6 kV. The stochastic cooling system currently used at present TARN, the band width of ∿ 100 MHz, the system gain of ∿ 150 dB, the pickup and the kicker being helical type, will be used for this pre-cooling purpose. After the acceleration, the high energy cooling system with the band width ∿ 1 GHz can be reasonably used to attain the momentum spread of ∿ $10^{-4}$. For intensities up to $10^{10}$ particles, emittances and momentum cooling time constants are of the order of 10 seconds. Electron cooling is most effective at lower energies, say ∿ 100 MeV/u and for beams which are already relatively cool. It can thus complement the stochastic system, especially at the experiments with the internal circulating beam of the momentum spread ∿ $10^{-5}$ and of the beam size smaller than a cm resulting from an equilibrium between the cooling and the heating through the internal target. A system for TARN II, with the length of ∿ 4 m, cooling time ∿ 10 seconds, is now being constructed. An internal gas jet target or polarized beam target will be used to perform the precise nuclear experiments taking advantage of the good beam energy resolution and 100 % duty of the circulating beam in the ring. With the wide band stochastic cooling system and the electron cooling system, both having the cooling time constants around 10 seconds, it is possible to use the thick target ∿ $10^{15}$ atoms/cm$^2$ and the luminosity up to $10^{31}$ (cm$^{-2}\cdot$s$^{-1}$) may be attained. The target should be placed in a low beta section to suppress the beam loss scattered by the target.

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