HEAVY ION ACCELERATOR AND COOLER - TARN2 -

Takeshi Katayama
Institute for Nuclear Study, Univ. of Tokyo
Midoricho, Tanashi, Tokyo 188, Japan

Abstract

On the basis of the successful experiments of beam accumulation and stochastic cooling at the TARN-1 ring, it was decided to construct the more powerful heavy ion ring TARN-2 which has the maximum rigidity of 7 T-m, corresponding to 1.3 GeV for proton and 0.45 GeV/u for ions of 1/2 charge-to-mass ratio. In this ring both the stochastic and the electron beam cooling methods are prepared to obtain the high resolution and small emittance beam. Especially the electron beam cooling has the advantage of low energy heavy ion beam cooling, and then the maximum e-beam energy 120 keV, corresponding to 200 MeV/u of ion energy, was selected. At present the injector is the sector focusing cyclotron with K = 67 which accelerates ion beams from protons to neon for TARN 2. In parallel with the construction of TARN 2, the heavy ion linac is now being constructed. The first part of the linac is an RFQ with the energy of 800 keV/u which was successfully tested with proton beam acceleration. After boosting up the ion energy to around 3 MeV/u by the drift tube linac, this system will take the place of injector for TARN 2. In this case the heavy ions up to Xe will be accelerated and cooled in the ring. In this paper, the status of construction of TARN 2 including the linac system will be presented .

Introduction

Much interest has developed recently in the fields of nuclear and atomic physics concerning the light or heavy ion storage ring with beam cooling devices. In this ring, the strong cooling devices such as stochastic and/or electron beam cooling, work together with internal targets, and it is expected that the extremely good energy resolution experiments would be performed such as threshold phenomena of pion production. Additionally, cooled heavy ion beams would open new fields of atomic physics such as radiative capture of cooling electrons, laser-induced electron capture and also the laser cooling. Corresponding to such physics interest, several storage ring projects are going on at Indiana, Uppsala, GSI, Heidelberg and INS, with the first beam scheduled in 1986-89. Among these projects the possible use for the basic study of heavy ion inertial fusion is planned at GSI and INS. Relatively low energy and high current heavy ion beams are cooled down in the ring, their emittance and momentum spread being reduced, then extracted with short pulse length. Extracted heavy ions will hit the target and a high-temperature, 10 eV plasma will be created. The behavior of ion beams in such a high-temperature medium, is a key issue which should be studied in the inertial fusion program with heavy ions.

TARN 2 is currently under construction and is scheduled for completion in 1987. The goals of the project are, firstly, to boost up the maximum beam energy to several hundreds MeV/u, secondly, to cool down the beam temperature in three phase spaces and, thirdly, to perform the nuclear and atomic physics as well as the application to other fields of scientific research.

Injector

In the present scheme, the injector of TARN 2 is a SF cyclotron with a K number of 67. This cyclotron can accelerate various kinds of ions from light ions like p, d, α ,to heavy ions like Fe^{6+} . However, due to the restriction of the present internal PIG ion source, the charge state of heavy ions is low and the output energy is correspondingly quite low. Among these heavy ions, Ne^{4+} will be the heaviest with a reasonable current of 1pμA and an energy of 2.6 MeV/u, which is adequate for acceleration in TARN 2. On the other hand ECR ion source is currently under construction for the cyclotron with the expectation of higher carge state heavier ion beams.[1] With the installation of this ECR ion source to the present cyclotron, heavier ions such as Ar, Ca and Kr will be extracted from the cyclotron with the intensity of around several μA.

The circulating beam current in the TARN2 is estimsted as follows. The peak current at the injection point is assumed at conservatively around 1 pμA (p, α) and 0.1 pμA (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 of 2 degrees in the RF acceleration field of the AVF cyclotron. The horizontal and vertical emittances are 10 π mm-mrad for p, d, α and 35 π mm-mrad for heavy ions. The acceptance of TARN 2 is designed at 400 π mm-mrad for the synchrotron mode operation, and the dilution factor during the process of multiturn injection is assumed at 2.5. Then the expected beam intensities are around 1 x 10^8 for p, d, α and 1 x 10^6 for heavy ions per pulse. However, if one uses both the horizontal and longitudinal phase spaces, the expected intensity will be increased by the order of two. This is mainly due to the fact that the AVF cyclotron beam has a very small longitudinal emittance of $\varepsilon_l = \Delta\phi\ (\Delta T/T) = 5 \times 10^{-4}$ rad.

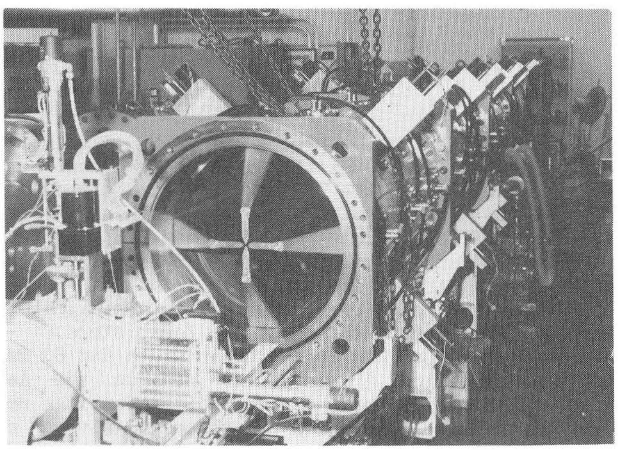
On the other hand, we are now constructing the heavy ion linear accelerator system which has a final output energy of 3 MeV/u; the first part of this system is now completed with an energy of 0.8 MeV/u. It is the four-vane type RFQ linac with the name of TALL.[2] The RFQ linac focuses the charged particles by RF quadrupole fields excited with four electrodes (or vanes) and accelerates them by the axial component generated with the scalloped modulation of the vane tip. This structure is very effective for the acceleration of high intensity beams in the low energy region.

Design parameters of TALL are given in Table 1. The RF system operates at the resonant frequency of 100 MHz and is driven with a single-loop coupler. The beam injection energy is 8 keV/u and the output energy is 800 keV/u, the total length being 725 cm. So far H^+ and H^{2+} beams were successfully accelerated, the measured output energy being 825 keV. The energy spread $\Delta T/T$ was measured at 1.6% (FWHM) and a transmission efficiency exceeding 90% was obtained for the H^+ beam of 10 μA. A view of the linac is given in Fig. 1.

Table 1 Design parameters of TALL

Ions (q/A)	1-1/7
Operating frequency (MHz)	100
Input Energy (keV/u)	8
Output energy (keV/u)	800
Total number of cells	300
Cell number of radial matching section	40
Vane length (cm)	725
Cavity diameter (cm)	58
Characteristic bore radius, r_0 (cm)	0.54
Minimum bore radius, a_{min} (cm)	0.29
Margin of bore radius, a_{min}/a_{beam}	1.15
Maximum modulation, m_{max}	2.5
Focusing strength, B_0	3.8
Maximum defocusing strength, Δ_b	-0.075
Synchronous phase, ϕ_s (deg)	-30
Intervane voltage for q/A=1/7 (KV)	81
Maximum field (KV/cm)	205 (1.8 Kilpat.)
RF power wall loss for q/A=1/7 (KW)	180
Transmission for input beam 0mA	0.94
2mA	0.91
10mA	0.63

Fig. 1 View of RFQ linac "TALL"



TARN 2 is installed in the new accelerator hall which became available by clearing up the old experimental hall of the FM cyclotron. (Fig. 2) Ions from the SF cyclotron are transported through the beam line, 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. Then ions are injected in TARN 2 by multi-turn injection. For heavier ions the injection energy is different for each ion species , whereas the proton injection energy will be constant at 20 MeV . During the process of passing through the thin carbon foil with a density of 50 $\mu g/cm^2$ at the stripper section, the beam quality will be degraded; for example, the emittance will increase due to the multiple scattering, and the energy spread will be enlarged by the straggling effects. As a most serious case, the Ne^{4+} beam of 2.6 MeV/u is examined which shows that the emittance of 20 π mm-mrad of the beam from the cyclotron will be increased to 35 π mm-mrad, and the energy straggling will be around 1 x 10^{-3} . The fraction of fully stripped ions is estimated at one third of the beam.

Beam life time at the injection energy is mainly determined, for heavy ions by the charge capturing process of fully stripped ions through collisions with

Fig. 2 Layout of TARN 2

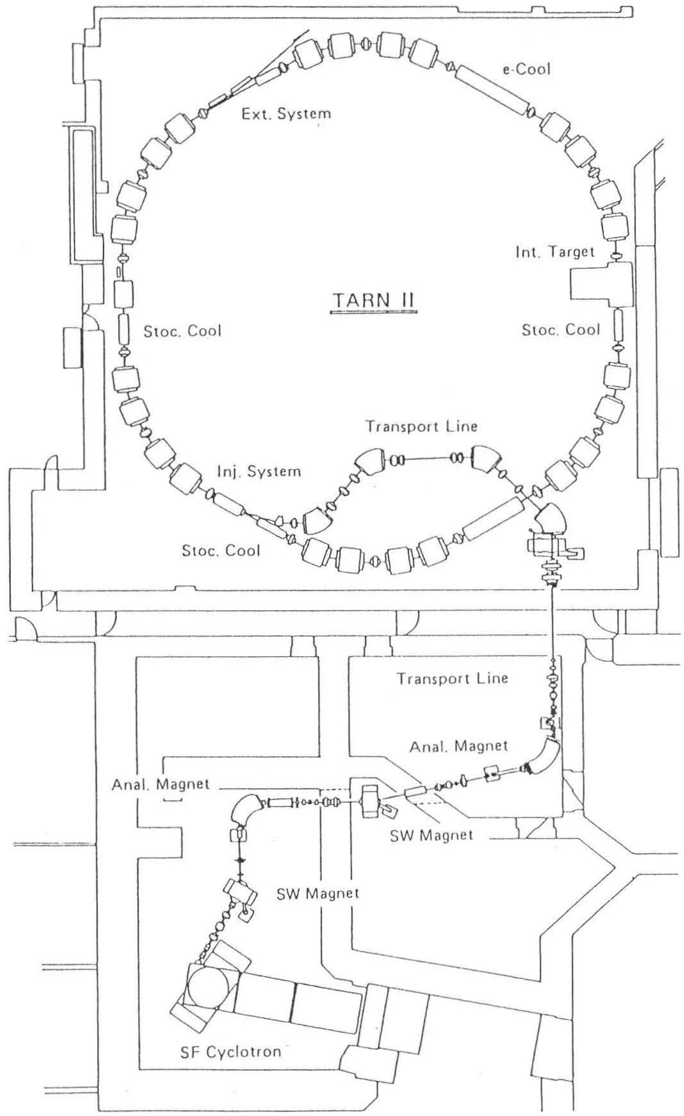


Table 2 Specification of TARN2

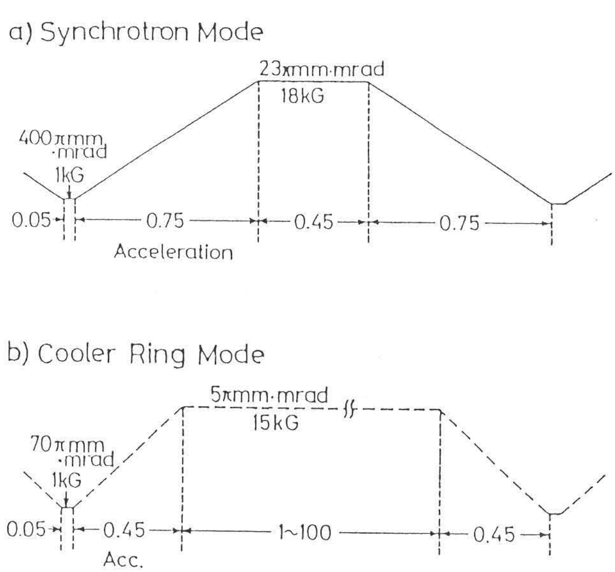
Maximum Beam Energy (MeV/u)	proton 1300
	ions with ε =1/2 450
Circumference (m)	77.761
Average Radius (m)	12.376
Radius of Curvature (m)	3.820
Focusing Structure	FBDBFO
Superperiodicity	6
" for Cooler Ring Mode	3
Betatron Tune Value	around 1.75
" for Cooler Ring Mode	around 2.25
Transition γ	1.87
Repetition Rate for Synchrotron Mode (Hz)	1/2
Maximum Field of Dipole Magnets (kG)	18
Deflection Angle of Dipole Magnets (°)	15
Maximum Gradient of Quadrupole Magnets (kG/m)	70
Revolution Frequency (MHz)	0.305-3.51
Acceleration Frequency (MHz)	0.61- 7.02
Harmonic Number	2
Maximum RF Voltage (kV)	6
Vacuum Pressure (Torr)	better than 10^{-10}

the residual gas and for the light ions, such as protons, by Rutherford scattering. Assming the vacuum pressure in the ring as 1x 10^{-10} Torr, the beam life is estimated as follows: 3300 sec for protons (20 MeV), 760 sec for C^{6+} (7.6 MeV/u), and 12 sec for Ne^{4+} (2.7 MeV/u). From this estimate of beam life at the injection energy, it is expected that there is enough time for beam manipulation, such as RF stacking or fast stochastic cooling, even at the flat-base injection period.

General Description of the Ring

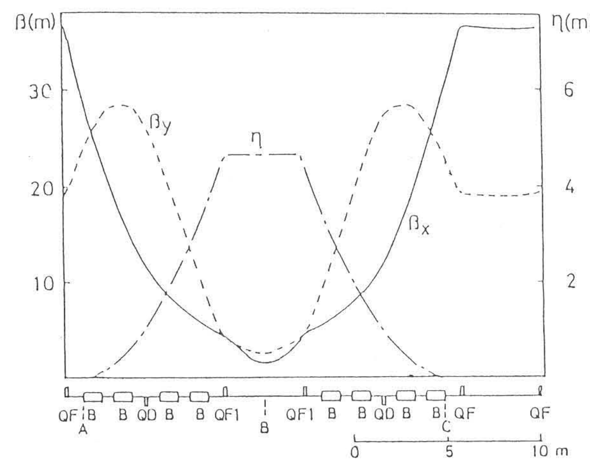
The ring will be used in three modes of operation: 1) normal synchrotron operation, 2) long spill operation, stretcher mode, and 3) cooler-ring mode. In the synchrotron mode, the repetition cycle is 0.5 Hz with the acceleration period of 0.75 sec, the flat-top of 0.5 sec and the falling period of 0.75 sec. This repetition rate is determined mainly due to the available 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. In the cooler-ring mode, the operation scheme will be nearly the same for the stretcher cycle while the strong beam cooling devices will be operated as well as the internal gas jet target. In Fig.3 two operation modes of synchrotron and cooler are given where the horizontal scale shows the time in second and the vertical the magnetic field strength and the estimated beam emmitance after the adiabatic damping through the acceleration.

Fig. 3 Operation modes of Synchrotron and Cooler Ring Modes



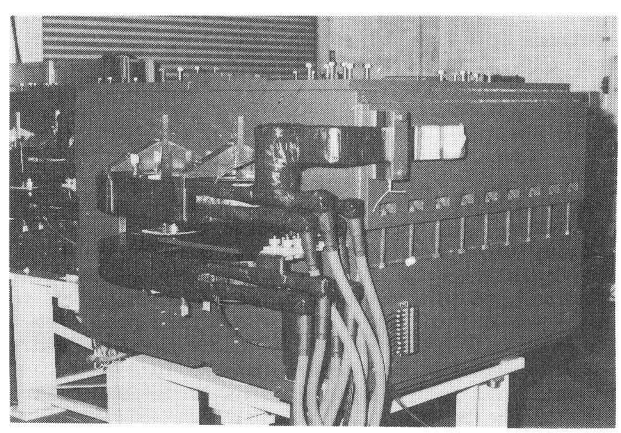
A set of lattice parameters for the stretcher and cooling modes is given in Table 2, and the lattice functions are shown in Fig.4. The circumference of 69.908 m is the maximum ring size that fits into the new accelerator hall and it is just the 17 times larger than the extraction orbit of the cyclotron. A symmetric, three-period lattice with the six long straight sections, each 4 m long, was adopted. Hence there are three dispersion-free straight sections and three large dispersion sections which is adequate for beam cooling and for the internal target experiments. In the dispersion-free straight section, 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, the internal target system and the electric inflector for the beam injection.

Fig.4 Lattice Function of Cooler Ring Mode



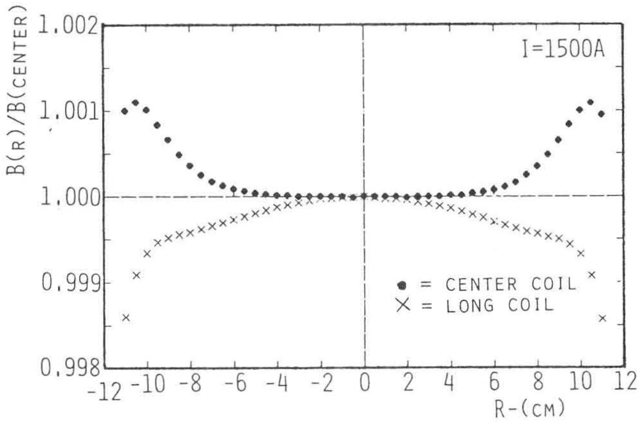
In the renovation process of TARN 1, all of the dipole magnets are rebuilt, while the quadrupole magnets being used in the TARN 1 ring will be used again for TARN 2. The magnetic structure of the new ring is made up of 24 dipole magnets and 18 quadrupole magnets. Each dipole magnet is an H type structure with a straight core length of 1 m.(Fig. 5) The edge shape at the end of the yoke is approximately a Rogowski curve cutting the yoke in four steps. The designed field region is 200 mm in width and 60 mm in vertical direction. In order to realize the large good field region for the wide excitation range up to 18 kG, the side pole edges are shaped to give a constant B curve. Also, small shims are attached to suppress the decrease of the magnetic field at the pole ends until the field is saturated.

Fig.5 View of Dipole Magnet



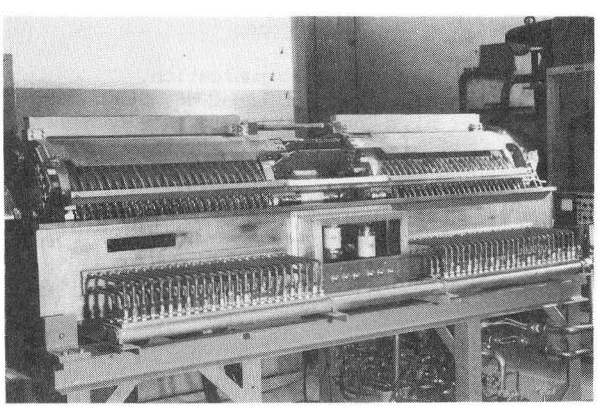
The magnetic fields has been measured for all of the dipole and quadrupole magnets.[3] Typically the magnetic fields strength of the dipole magnet is given in Fig. 6. where the excitation current is 1500 A coresponding to the proton beam energy of MeV. In the figure, black dots show the field shape at the center of magnet while the crosses show the integrated magnetic field strength B.l along the longitudinal direction. Clearly we can obtain the good field region, Δ (B.l)/B.l less than 5 x10 $^{-4}$, in the radial range of 10 cm.

Fig.6 Result of Field Measurement of Dipole Magnet



An RF system will accelerate the ions 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 1300 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 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 (Fig.7). 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.[4]

Fig.7 View of RF Cavity

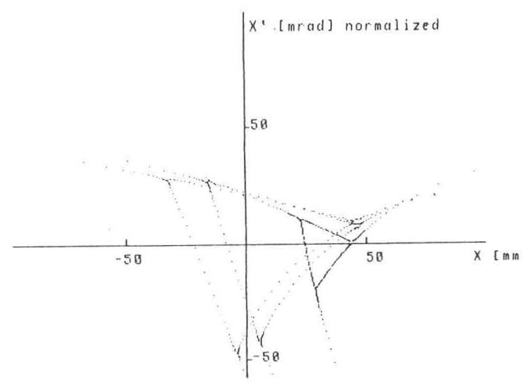


The residual gas has several effects on beams circulating in TARN 2, namely, 1) the charge-capturing process of fully stripped heavy ions leads to beam loss, 2) multiple Coulomb scattering of light ions determines the beam life in the ring, 3) contribution to background when the jet target experiments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

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

On the assumption that the momentum spread at the extraction energy 1.3 GeV is 0.2% and the horizontal beam emittance is 54 π mm.mrad, the computer simulation has been performed.[5] The resonance operating point is selected at 1.6755 and the chromaticity is -0.26. The results show that the maximum separatorix area is adjusted to cover the beam emmitance of 54 π mm.mrad for the momentum spread of 0.2%. In Fig. 8 three separatrix and outgoing trajectories at the electric septum position are given. Three separatrixes are corresponding to the momentum spread of 0, 0.2, and 0.6%, respectively. The turn separation are 8.4, 7.0 and 4.2 mm, respectively. The emmitance of the extracted beam is about 0.3 π mm.mrad with the extraction efficiency of 85%.

Fig.8 Simulation of 1/3 Resonance Extraction

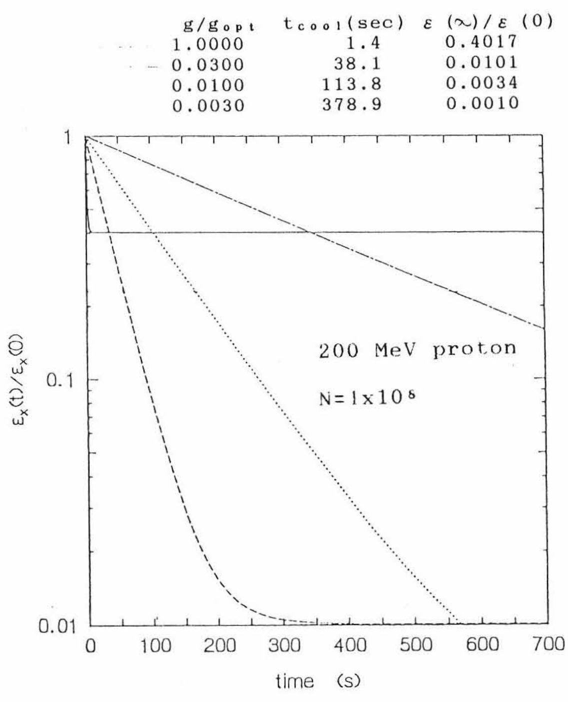


Beam Cooling

Both stochastic and electron beam cooling will be used to obtain the high quality beam. For the stochastic cooling, two systems will be used, one being the pre-cooling and the other the high-energy cooling. With a pre-cooling 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 pre-cooling is indispensable to keep the accelerating RF voltage as reasonably small as possible. The RF stacked beam will have a momentum spread of 1 %, and it should be decreased to 0.2 % to accelerate the beam within the designed RF voltage of 6 kV. The stochastic cooling system[6,7] used at TARN 1, with a band width of 100 MHz, a system gain of 150 dB, the pickup and the kicker being of the helical type, will be used for this pre-cooling purpose. After the acceleration, the high-energy cooling system with the band width of 1 GHz can be reasonably used to attain the momentum spread of 10^{-4}. In the high-energy cooling system, pickups and kickers are of the loop-coupler type with 16 pairs of couplers of $\lambda/4$ length. The calculated coupling impedance is around 100 Ω in the concerned frequency region of 1 to 2 GHz. The pre-amplifier is composed of Ga As Field Effect Transistor cooled down to the temperature of liquid nitrogen. The expected noise figure (NF) is around 0.5 dB. With these parameters the optimum or fastest cooling time is 33 msec when the system gain should be 197 dB with the unrealistic power of 2.5 GWatt. With the reduction of gain to 137 dB, the cooling time increases up to 33 seconds, with the power of 2.5 kW which would be a good compromise between the cooling time and needed RF power. In this case, the saturated rms momentum spread is expected to be 5×10^{-5}.

The variation of horizontal beam emittance $\varepsilon(t)$ is calculated and is given in Fig. 9 where the normalized beam emittance $\varepsilon(t)/\varepsilon(0)$, $\varepsilon(0)$ being the initial emittance, is given with time for various system gains. With the reduction of system gain from the fastest cooling gain, g_{opt}, by 30 dB, the final $\varepsilon(t)/\varepsilon(0)$ is 10^{-3} in spite of the long cooling time of 380 seconds.

Fig.9 Variation of Normalized Horizontal Emittance with Stochastic Cooling



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 in the experiments with the internal circulating beam where the momentum spread is 10^{-3} and the beam size smaller than one cm resulting from an equilibrium between the cooling and the heating through the internal target.

The main parameters of the electron cooling system are listed in Table 3. The system is designed to cool down the ions from H^+ to Ne^{10+} up to 200 MeV/u, limited by the maximum electron energy of 120 keV. The electron energy is variable from 12 to 120 keV, and the maximum current density 0.5 A /cm² is available at voltages higher than 60 keV whereas the current at the lower collector voltage is determined by the perveance. The length of the interaction region is 1.8 m which is limited by the length of the straight section 4 m. As the beam size at the cooling section after the acceleration is less than 50 mm, the cathode diameter is designed to be 50 mm, which is a type of flat cathode rather than a spherical one. The cathode is immersed in the uniform solenoidal field having a maximum field strength of 1 kG. An example of electron trajectories in the region of the electron gun is given in Fig.10 where the collector voltage is 110 keV, the electron current is 10 A, and the perveance is 0.688 $A/V^{3/2}$. The transversal electron temperature is assumed in this case to be less than 1 eV. A layout of the electron cooling device, the so-called U scheme, is shown in Fig.11 where the electron beam is injected and ejected over the beam line of the ring.

Table 3 Electron cooling parameters

Maximum working energy	ions (MeV/A)	200
	electron (KeV)	120
Cooled ions		$H^+ - {}^{20}Ne^{10+}$
Gun optics		
Pierce type + resonance focussing electrode		
Length of interation region (m)		1.8
Maximum electron current density (A/cm²)		0.5
Cathode diameter (mm)		50
Maximum current (A)		10
Maximum solenoid field (G)		1000

The electron cooling process has been simulated[8] with the help of the CERN program SPEC. A typical example of the time evolution of the ion distribution in the (X,Y) space and (X,Δ p/p) space is given in Fig.12. As can be seen, a drastic reduction of beam size and momentum spread is expected within several seconds.

Acknowledgement

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Fig.10 Electron Trajectories in the Gun

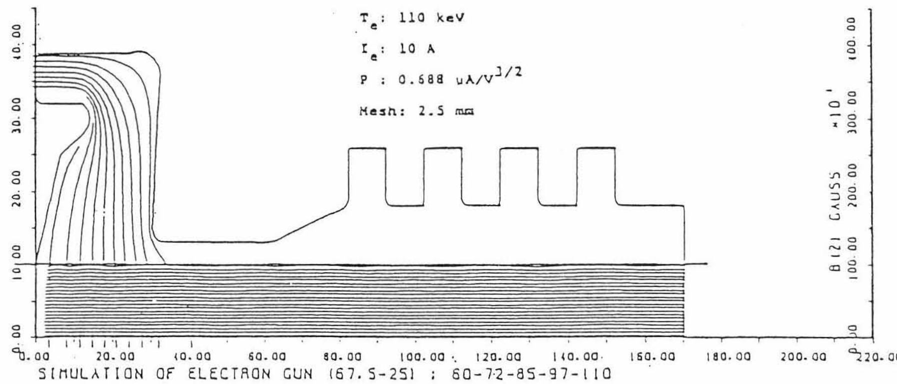

Fig.11 Layout of Electron Cooling System

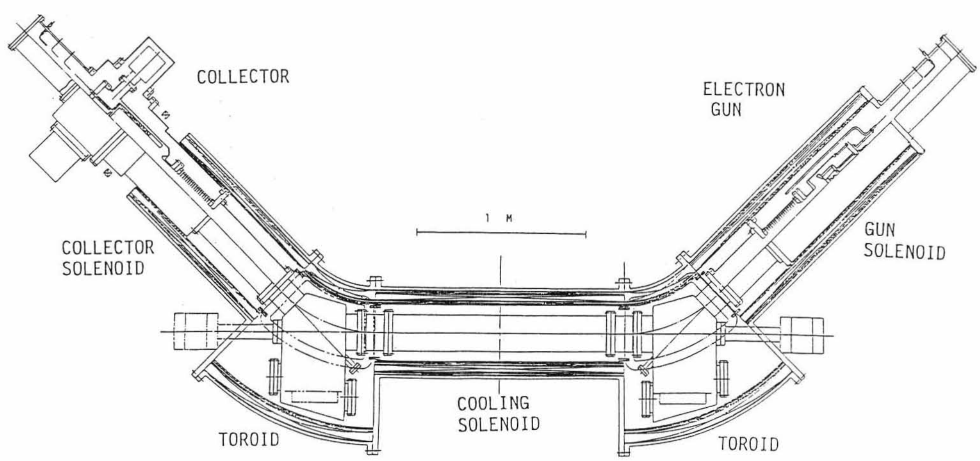

Fig.12 Time Evolution of Three Phase Space Area of 100 MeV Protons