BEAM ACCUMULATION AND MOMENTUM COOLING AT TARN

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TARN is a low energy, around ten MeV/nucleon, ion storage ring aimed at the technical development for the high energy ion accelerator project at INS. This storage ring can accumulate the beam both in the longitudinal and transverse phase spaces from the injector cyclotron. Up to now, proton, H_2^+, α and $^3He^+$ beams have been stored. Twenty turn beam are injected in the betatron phase space area of 87 πmm·mrad by the multiturn injection method and 15 pulses are RF stacked in the momentum space Δp/p of 2.2%. Overall stacking number is then attained at around 300 turns. RF stacking is performed with the repetition rate of 30 Hz and it requires ∿ 0.5 second to fill the two phase spaces with beam.

Stochastic momentum cooling experiment was applied to a proton beam of 7 MeV. Beam signal pick-up and kicker are traveling wave type couplers with inner conductors of helices. With adjustment of the amplifier gain to 107 dB, the cooling time was measured at ∿ 20 seconds.

Introduction

The idea of ion beam accumulation and cooling has been developed so far in the use of high energy proton or antiproton rings to perform the particle physics. Recently the application of such a technique to the storage ring of light or heavy ions, is enthusiastically planned or discussed at many laboratories. The purpose of their projects are; Several tens mA of circulating cooled ion beam would be used for nuclear physics experiments, being expected to be high resolution and high luminosity. Storage and cooling of unstable nuclear beams produced in the process of high energy heavy ion collisions, would be used for developing the nuclear physics of new phase. Besides the use for nuclear physics the storage ring of high current heavy ion beam with cooling devices could demonstrate the feasibility of the driver system for heavy ion fusion.

Test Accumulation Ring for Numatron, high energy heavy ion accelerator project in our country, TARN has been constructed for developing exclusively accelerator technologies related to the project. It can accumulate the beam from the cyclotron with K number of 67, being expected to verify the concept of installation of the accumulator ring between the injector and the main synchrotron to boost up the intensity.

The stochastic cooling experiments was also performed for the low energy proton beams to decrease the momentum spread of the stacked beam. The ring is not designed for the purpose of cooler ring and has not the straight section with dispersion-free. However the trial of momentum cooling at the cost of emmitance growth, gives the useful data for the construction of improved TARN, TARN II which is now under construction at INS for the further research of accelerator physics and possibly for nuclear physics as the acceleration and cooler ring.

In this paper the summary of beam accumulation experiment and the result of stochastic cooling experiment are presented.

Beam Accumulation

General Description of the Ring

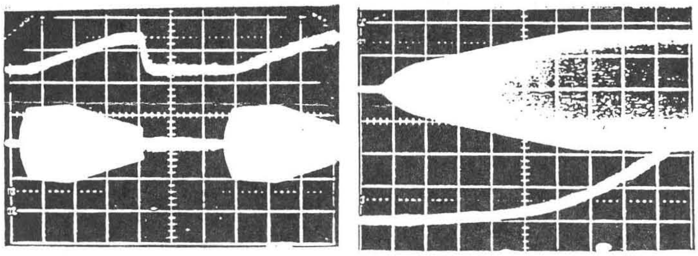
Details of the ring can be found in the references,[1,2] then fundamental idea of beam accumulation method is shortly described here. In Table 1 main parameters of TARN are listed.

Table 1 TARN Parameters

Max Beam Energy (ε = 0.3)	8 MeV/u
Max Magnetic Field	9.0 kG
Radius of Curvature	1.333 m
Average Radius	5.06 m
Useful Aperture	45 × 190 mm²
Revolution Frequency	1.3 MHz
Betatron ν Values (ν_x, ν_z)	2 ∿ 2.5
Transition γ	1.894
Injection Method	Multiturn
Momentum Spread of the Stacked Beam	2.46 %
Repetition Rate of RF Stacking	30 Hz
Vacuum Pressure	1×10^{-10} Torr

Magnetic focusing system of the ring are composed of eight bending and sixteen quadrupole magnets with a lattice structure of FODO type. Additionally twelve sextupole magnets of two sets, are installed for chromaticity correction. Eight straight sections, each of which is 1.80 m long, are served for various instruments of beam injection, stacking and beam diagnostic systems. Beams are transported from the cyclotron to the ring by the distance of ∿ 40 m and the momentum is analyzed to ∿ 1×10^{-3} through the line. A kicker magnet located in the transport line, shapes the beam pulse width to ∿ 80 μs suitable for multiturn injection. By the use of an electrostatic inflector and two bump magnets, beams are multiturn injected in the betatron phase spaces.

The injected beam is completely debunched at ∿ 250 μs after the injection due to its intrinsic momentum spread. The RF voltage is then increased from zero to 77 V for proton beam, adiabatically in order to capture the coasting beam into the separatrix, of which the area is equal to the beam longitudinal phase space area, 100 keV·rad. In this capture process, RF frequency is kept constant at 8.012 MHz, seven times the revolution frequency of particles on the injection orbit and hence the synchronous phase angle ϕ_s is 0 degree. Period of phase oscillation is 0.45 ms at the end point of capture process and the period for increasing the voltage from zero to 77 V is chosen as 0.5 ms. Computer simulation shows that the rising period of nearly phase oscillation period can achieve the highest capture efficiency (∿ 80%), whereas too shorter or longer period fail to trap the beam in the separatrix. In Fig.1 the functions of RF voltage and frequency are illustrated and parameters of RF stacking dynamics are given in Table 2. After the capture process (region I), synchronous phase is increased from 0° to 15° (region II), kept constant as 15° (region III) and finally changed back to 0° (region IV). Through the whole process, separatrix area is kept constant at 100 keV·rad in order to prevent the dilution in the longitudinal phase space.



(a) (b)

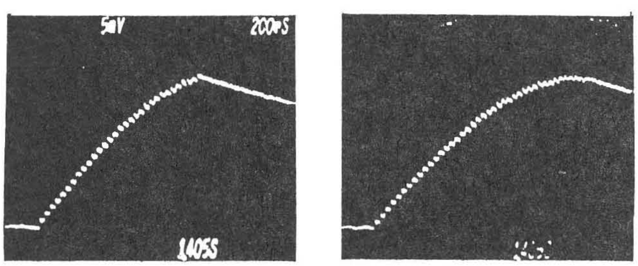
Fig.1 RF frequency and amplitude modulations for RF stacking. Horizontal scales are 5 ms/div (a) and 1 ms/div (b), respectively.

Table 2 RF Voltage and Frequency Parameters for Proton

Region	I	II	III	IV
Voltage V (Volt)	0 → 77	77 → 224	224	224 → 77
Frequency Shift Δf (KHz)	0	13.7	166	120
Synchronous Phase ϕ (Degree)	0	0 → 15	15	15 → 0
Time Derivative of RF Frequency Shift Δf/Δt (MHz/sec)	0	0 → 27.06	27.06	27.06 → 0
Period τ (ms)	0.5	1.0	6.0	8.0
Fractional Momentum Change Δp/p (%)	0	0.24	3.21	5.35
Change of Closed Orbit ΔR (cm)	0	0.37	4.86	8.10
Fractional Frequency Change Δf/f (%)	0	0.17	2.25	3.75

Beam Stacking[3]

The RF stacking is repeated at 30 Hz and the beam intensity increases linearly up to the stack number of 30 (Fig.2-a), while it shows the saturation at more stacking (Fig.2-b). In these figures, beam current is measured by use of the current transformer of permalloy with the sensitivity of 2.5 μA/mV and time constant of 4 sec. On the other hand, spatial profiles of stacked beam is measured by the movable scintillation monitor as in Fig.3. From the data of beam profiles an amplitude of betatron oscillation x_β is measured at 17 mm and the emittance of the multiturn injected beam is deduced at 87 πmm·mrad, when the emittance of injected beam is 3.8 πmm·mrad.



(a) (b)

Fig.2 Beam current increases with RF stacking. Stacking number is 30 (a) and 40 (b), respectively. Current sensitivity of the monitor is 12.5 μA/div and horizontal scale is 200 ms/div.

The momentum spread of the stacked beam was measured with the Schottky signal which was obtained through the pickup system for the stochastic cooling. The same technique was applied also for the measurement of momentum spread of the multiturn injected beam from the cyclotron. In Fig.4 the Schottky signal of the harmonic number of 79 is presented, where one can see the full width of frequency spread Δf/f as 0.0022 and then the momentum spread Δp/p of the injected beam is deduced as 0.0031.

Working Line and Beam Life

With RF knock out method betatron tunes ν_x, ν_y are measured to be extended from the injection point to the stack top due to finite chrmoaticity size. (Fig.5) Normal operation line A crosses the fifth order resonances $n\nu_x + (5-n)\nu_y = 11$ and the fourth order resonance $4\nu_x = 9$. Beam loss due to the excitation of these resonances is not observed during the beam life, order of ∿ 500 seconds. However, in the line B where the tune covers longer band due to the excitation of sextupole magnets, it crosses the fourth order sum resonance and the stacking efficiency is not so good as in the case of line A. From these measurements, it is found that resonances higher than fifth order do not largely disturb the beam at TARN. Natural chromaticities ξ_x and ξ_y are measured at - 1.93 and - 0.64, while the calculated values with SYNCH program are - 4.54 and - 1.26, respectively.

The e-folding beam life of 7 MeV proton was measured for various vacuum pressure (Fig.6) and it is usually around 400 seconds as the vacuum operation condition is ∿ 1×10^{-10} Torr. The limitting factor of the beam life is mainly the Rutherford scattering with the residual gas and the resonance effect or the coherent, incoherent beam instabilities do not affect the beam life in the present beam current.

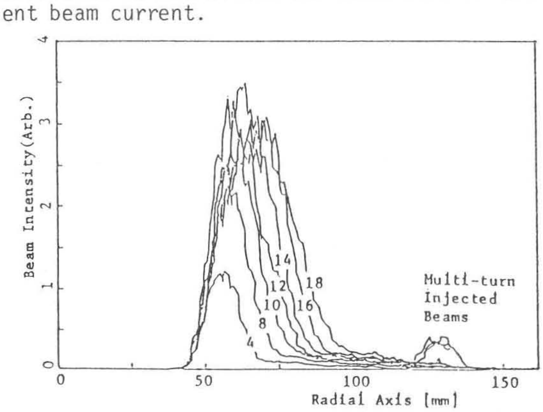


Fig.3 Beam profiles of multiturn injected and RF stacked beams. Each number in the figure corresponds to the stacking number.

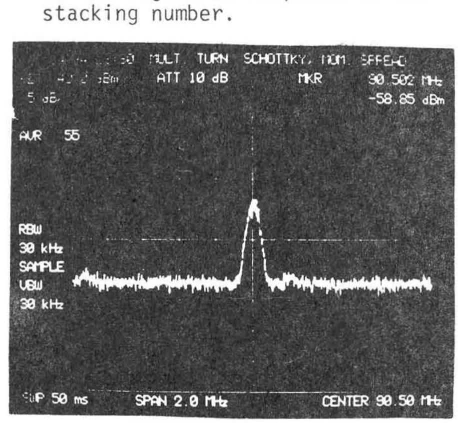


Fig.4 Schottky signals of the multiturn injected beam. Corresponding momentum spread is 0.31%.

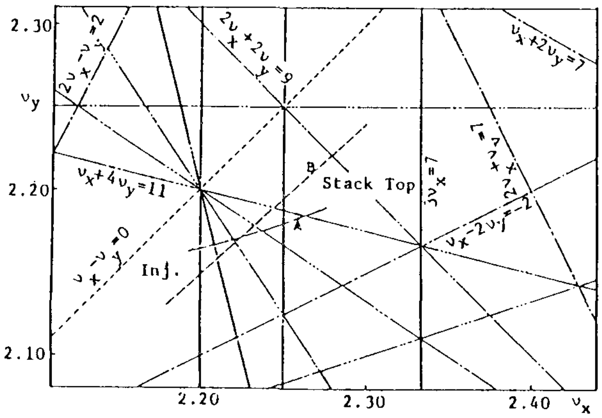


Fig.5 Tune diagram for beam stacking. Working lines A and B correspond to the conditions with sextupole magnets on and off, respectively. Notations of single particle resonances are as follows. ---- 2nd, —·—·— 3rd, —··— 4th and —···— 5th orders.

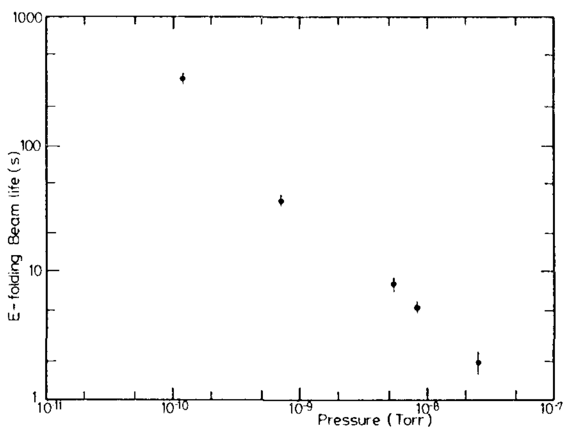


Fig.6 Proton beam life versus vacuum pressure in the ring.

Momentum Stochastic Cooling

The cooling was applied to a proton beam, since its life time is longer and the intensity is higher than other ion beams. As two straight sections of about 1 m long are available for the pickup and the kicker, only momentum cooling with the notch filter method is applied without transverse cooling. The blow-up rate of the horizontal emittance was calculated, and we consider that this is not negligible.

The pickup and the kicker are identical 75 cm long traveling wave type couplers with inner conductors of helices. The coupling impedance of the pickup and the shunt impedance of the kicker is high in a frequency range of 20 MHz through 110 MHz. Frequency dispersion $\tilde{\eta}$ is as large as 0.705 at TARN, so the initial momentum spread of the beam is set at 1% to avoid Schottky band overlap in the concerned frequency range. The cooling rate was calculated with characteristic values of the equipment of the feedback system. The optimized cooling time is calculated at 40 s with parameters in Table 3.

The measured beam life time is longer than 400 s, but is not much longer than the cooling time. Therefore the adjustment of the amplifier gain is important under the condition of the short beam life time and the betatron oscillation blow-up.

Table 3 Main parameters of cooling at TARN

kinetic energy (T)	7 MeV
$\beta = v/c$	0.1215
number of protons (N)	1×10^8 (18 μA)
revolution frequency (f_0)	1.12 MHz
frequency dispersion, $(\Delta f/f)/(\Delta p/p)$ ($\tilde{\eta}$)	0.705
dispersion function at the kicker (η)	1.3 m
momentum spread in full width ($\Delta p/p_0$)	0.01
system bandwidth (W)	20 - 110 MHz
Schottky current/band (I_S)	2.53 nA
horizontal rms emittance (ε)	80 πmm·mrad
optimized cooling time (τ_0)	40 s

Another restriction on the amplifier gain is the stability condition of the beam under coherent modulation in the cooling process. This condition requires the absolute value of the product of the amplifier gain and the beam transfer function to be smaller than unity. The beam transfer function was calculated for our case, and the stability condition turned out to be satisfied.[4]

Pickup and Kicker

The traveling wave structure with inner conductor of helix was chosen as pickup and kicker electrodes, because it is simple in structure, and has enough high coupling impedance and shunt impedance in the concerned frequency range.[5] Comparison of performances between the array of short gaps with ferrite cores and helical electrode has been made.[6]

In the sheath helix model, the coupling impedance Z of the electrode is given by[7]

$$Z = \frac{\gamma_0{}^2\gamma_S J_0(\gamma_S a)}{2\pi\varepsilon_0\omega a(\gamma_0{}^2+\gamma_S{}^2)J_1(\gamma_S a)} \times \frac{I_0(\gamma_0 b)K_0(\gamma_0 d) - I_0(\gamma_0 d)K_0(\gamma_0 b)}{I_0(\gamma_0 a)K_0(\gamma_0 d) - I_0(\gamma_0 d)K_0(\gamma_0 a)} ,$$

where γ_S and γ_0 are wave propagation constants in the beam and pipe, respectively, a, b and d represent the radii of beam, helix and pipe. On the other hand, propagation constant γ in the TW structure is the function of frequency and is not always equal to the wave propagation constant γ_0. Thus the final coupling impedance Z_C including this effect is deduced as

$$Z_C = Z\ell \left|\frac{\sin A}{A}\right| ,$$

where

$$A = -\frac{\ell}{\ell_C}\sin^{-1}\left(\frac{\omega}{\omega_C}\right) + \frac{\Omega\ell}{2\beta c}$$

represents the difference of propagation constants of wave and electrode: ℓ and ℓ_C are respectively lengths of the electrode and the unit cell, and ω_C is the cut-off frequency of the traveling wave structure. Parameters of the pickup are given in Table 4, and the calculated coupling impedances are shown in Fig.7.

Table 4 Characteristic values of the pickup and the kicker.

effective radius of helix	b = 8.10 cm
effective radius of pipe	d = 12.54 cm
cutoff frequency	f_C = 320 MHz
characteristic impedance	Z_0 = 110 Ω
total length	ℓ = 75.2 cm
cell length	ℓ_C = 6.1 cm
coupling impedance at 100 MHz	Z_C = 500 Ω
shunt impedance at 100 MHz	Z_S = 18 kΩ

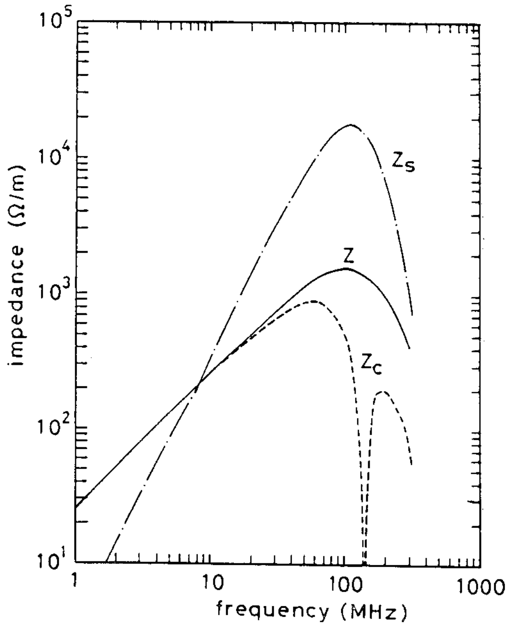


Fig.7 Calculated shunt impedance of the kicker (Z_S), the pickup coupling impedance without the effect of the difference of propagation constants (Z), and the one with the effect (Z_C).

The kicker has the same structure as the pickup, and the phase velocity is just matched to the beam velocity in the frequency range used at the present stochastic cooling. The shunt impedance of the kicker is calculated as in Fig.7 on the assumption that the wall loss is negligible.

Pickup and kicker electrodes are designed to have a characteristic impedance of 110 Ω and the impedance transform between the electronics system of 50 Ω and the electrodes has been made with use of wide band transformer.

Electronics System

According to the designed values of the pickup coupling impedance and the kicker shunt impedance, the optimum cooling rate is available, when the kicker is supplied with 72 mW power for the case of Table 3.

This power is 2×10^{11} times larger than the amplifier noise, so the amplifier system must be capable of a total gain of 113 dB at maximum. The electronics system from the pickup through the kicker is shown in Fig.8.

The preamplifier is Trontech W500EF, which is low-noise (NF = 1.3) and high-gain (64 dB) in a wide range of 5 - 500 MHz. The amplifier is mounted in a shielding box with a power divider and an attenuator. One of the output signal of the divider is fed to the following notch filter, and the other is sent to a spectrum analyzer (Takeda TR4172) in the control room.

The notch filter is a shorted 120 m long Hitachi HF-39D co-axial cable. Its attenuation at 100 MHz is 0.72 dB/100 m. The resonant frequency of the 120 m cable is 1.1458 MHz. The fine tuning of the frequency is done by adding short cable or using length-variable co-axial line of a trombone type. The cable is sandwitched by two 100 Ω resistors. Its amplitude and phase characteristics are used to provide correction voltage proportional to frequency deviation.

The output signal is fed to an intermediate amplifier, Trontech W500C (gain = 42 dB and NF = 1.4 at 5 - 500 MHz). The total gain of the whole amplifier system is adjusted by a variable attenuator. The time delay from the pickup to the kicker must be 335 ns. A 70 m delay line is inserted to get a delay of 253 ns. The attenuation of the cable is 4.5 dB at 100 MHz. The 50 W power amplifier (ENI AS-5500) gains 50 dB in a frequency range of 1.5 - 400 MHz.

Experimental Results of Cooling

The first cooling experiment was performed January, 1984 with use of 7 MeV proton beam. The pickup and kicker were installed at the straight sections number 4 and 7, respectively as in Fig.9. Previous to the cooling trial, the sensitivity of the pickup was measured as in Fig.10. In the figure we can see that the sensitivity increases as the function of frequency up to around 100 MHz, whereas the first dip exists at around 125 MHz. Comparing this experimental data with the calculated one as given in Fig.7, the general tendency is in agreement with each other.

Stochastic acceleration with the notch filter removed can give us the nice information on the time delay between the TOF of beam from the pick up to the kicker and the propagation time of the Schottky signals through the electronic system.[5] The stochastic acceleration rate dE/dt at the system gain of 98 dB is plotted as the timing delay in Fig.11, where we can see that the fine adjustment within the accuracy of ± 2 ns is necessary for the optimum cooling. The observed acceleration rate is used for the estimation of the product of the coupling impedance of pickup and the shunt impedance of kicker.

Momentum cooling with the active gain of ∿ 100 dB for the beam current of 12 μA, 6.6×10^7 protons was performed. An example of the results is given in Fig.12 and Table 5 where longitudinal Schottky scans before and after the cooling are illustrated. The initial momentum spread of 1.4% was reduced to 0.4% with ∿0.5 Watts of power into the kicker. Cooling time is around 20 seconds which is roughly in agreement with the designed value. A primary factor determining the limiting of the final momentum spread is the depth of notch filter which is around 15 ∿ 20 dB

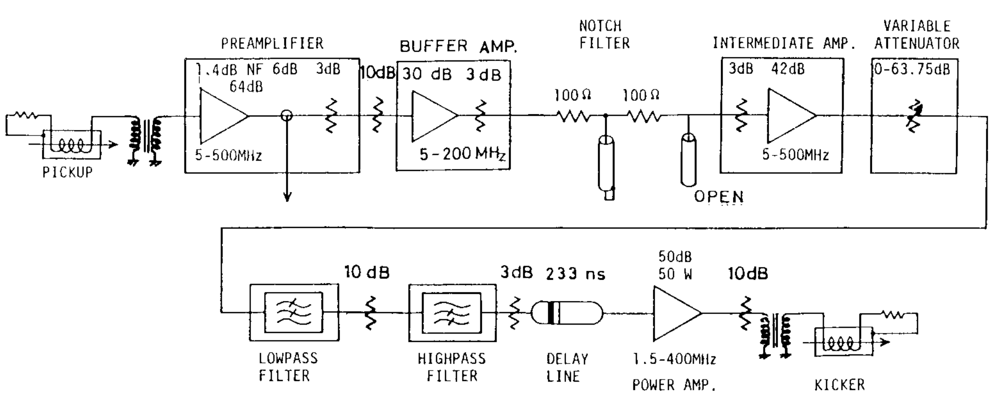


Fig.8 Block diagram of electronic system for momentum cooling.

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in the concerned frequency range. The compensation of finite attenuation in the notch is an essential in achieving a narrow final momentum width of the beam.

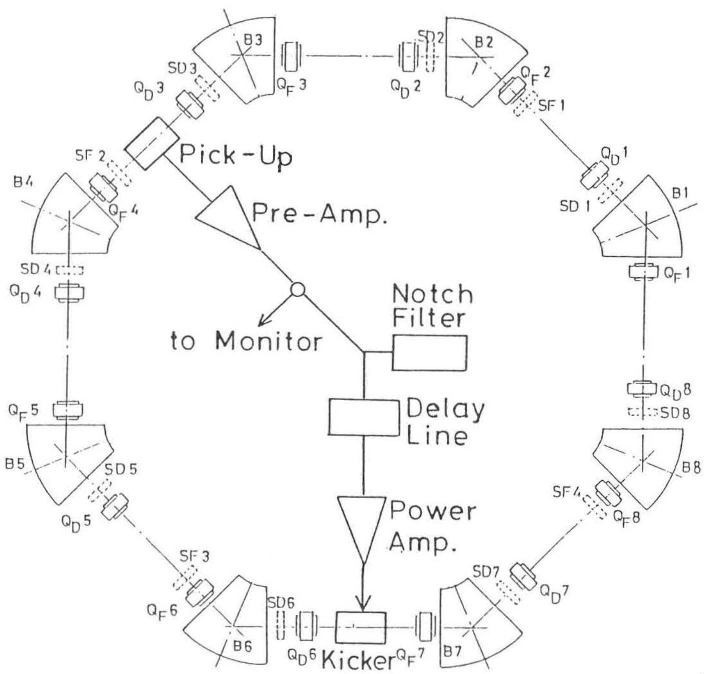

Fig.9 Layout of the equipments of the cooling system

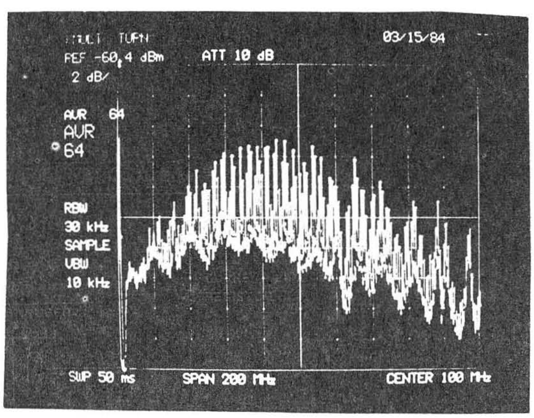

Fig.10 Pickup sensitivity was measured as the function of frequency. Horizontal span width is 200 MHz and first dip is observed at 125 MHz.

Table 5 Summary of the cooling parameters

Beam	7 MeV proton, β = 0.12
Revolution frequency	1.14 MHz
Intensity	12 μA, 6.6 × 10^7 protons
$(\Delta f/f)(\Delta p/p)$	0.705
System gain	107 dB
Band width	20 - 100 MHz
Method	Double notch filter
$\Delta p/p$ in full width	1.4% (initial)
	0.5% (final)
Cooling time	∿ 20 s

When one increase the active gain, the beam current after the cooling was reduced as in Fig.13.

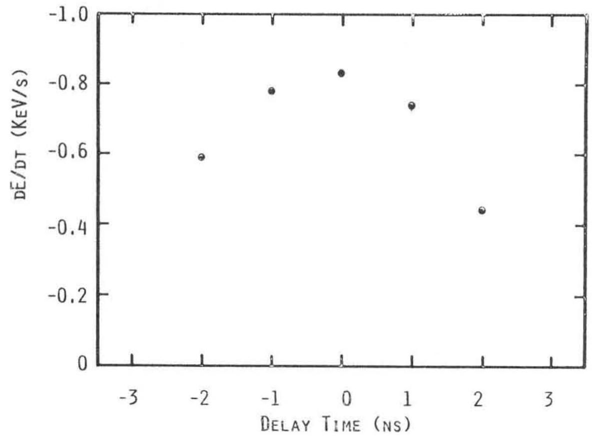

Fig.11 Stochastic acceleration rate dE/dt is plotted as the function of time delay.

The survival rate η is constant ∿ 0.6 below the system gain of 103 dB whereas it rapidly decreases when the gain is increased to ∿ 110 dB. At present the explanation of this intensity reduction is not so clear, however it is anticipated that the horizontal emittance growth due to the finite dispersion at the kicker, would cause the beam loss for the high gain condition, whereas the beam loss at the low gain is attributed to the beam life due to the Rutherford scattering with the residual gas.

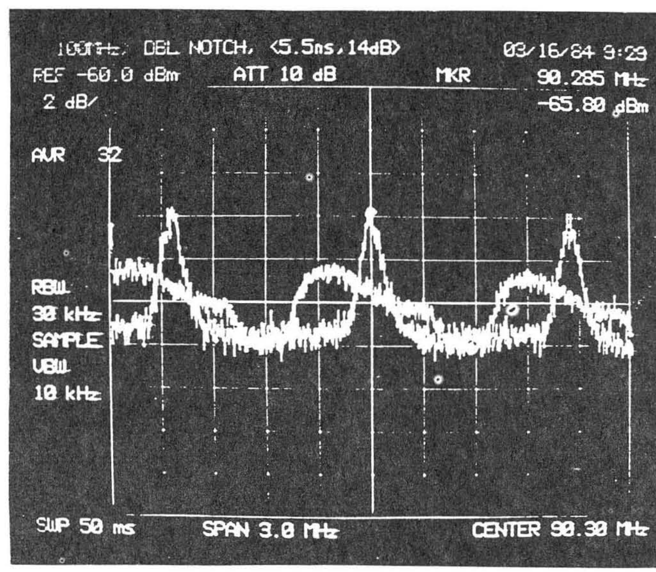

Fig.12 Typical example of the momentum cooling. Longitudinal Schottky scans before and after the cooling at the harmonic number 79.

Conclusive Remarks

Cyclotron beams were successfully accumulated in the horizontal and longitudinal phase spaces and their momentum spread were cooled down with the simple devices. The cooling experiment is still preliminary but the fundamental technique has been established.

On the basis of these achievements of the accelerator studies, we have decided to construct the improved TARN, TARN II which can accumulate and accelerate the beam from the cyclotron and/or the planned injection linac. The maximum $B\rho$ of TARN II is 7 T·m and the corresponding proton beam energy is 1.3 GeV.

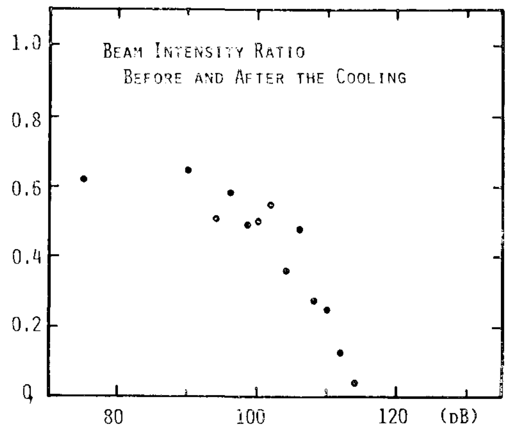

Fig.13 The ratio of beam intensity before and after the cooling is plotted versus the system active gain.

Cooling devices of both the stochastic and electron beam will be used to obtain the high quality ion beam. This new ring is now under construction and the first beam will be accelerated and cooled in 1986.

Acknowledgment

The main contributors of the cooling experiment are N. Tokuda, M. Takanaka, A. Noda, H. Yonehara, T. Hattori, M. Yoshizawa, S. Watanabe and the author. Beam accumulation and cooling experiments have been performed as the coworks of the member of accelerator development division at INS. It is a pleasure for the author to thank all of them for their collaborations and assistances.

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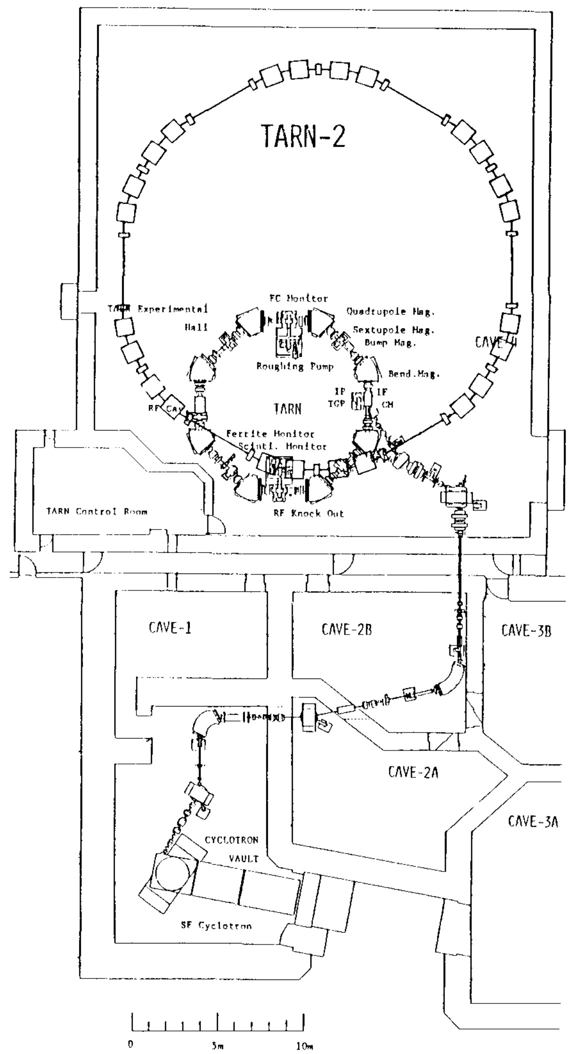

Fig. 14. Layout of SF cyclotron present TARN and TARN-2.