STUDY OF BEAM DYNAMICS AT COOLER SYNCHROTRON TARN-II

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ABSTRACT

Several kinds of beam diagnostic instruments, have been developed at cooler-synchrotron TARN-II. These are intended to study beam dynamics at low beam current of several microamperes and then have high sensitivity of good S/N ratio. In addition, the acceleration system, especially low level RF system, has been improved to attain the maximum beam energy. With the successful performance of these instrumentations, the study of beam dynamics are presently being carried out. For example, the synchrotron acceleration of the light ions was achieved up to 220 MeV/u without any beam loss.

1. INTRODUCTION

TARN-II is a cooler-synchrotron with a maximum magnetic rigidity of 5.8 Tm, corresponding to 1.1 GeV for protons and 0.37 GeV/u for ions of charge-to-mass ratio of 1/2.[1] The ring has a circumference of 78 m and FBDBFO magnetic structure with a superperiodicity of 6. An injector is a sector-focusing cyclotron with K number of 68 which can accelerate a variety of ion beams supplied by ECR or PIG ion sources. Normally the intensity from the cyclotron is as low as several microamperes for light ions and almost two order smaller for heavy ions. To handle such a low current beam in the ring, we have developed several kinds of beam monitors[2] for the detection of beam positions, beam phase , DC beam current and Schottky signals. With the successful performance of these diagnostic instrumentations, the synchrotron acceleration, for example, was achieved up to 220 MeV/u without any beam loss. The vacuum, ion source and control system have been improved to perform an extended study of beam dynamics. The present paper summarizes the recent experimental results of beam dynamics studies at cooler-synchrotron TARN-II.

2. BEAM DIAGNOSTIC INSTRUMENTS

A permalloy core monitor, a travelling wave monitor, a DC beam monitor and electrostatic beam monitors, are used to measure the beam dynamics during injection, accumulation and acceleration batch. The layout of beam diagnostic instruments is given in Fig. 1.

The permalloy core monitor is placed at the straight section, S5. It comprises laminated permalloy tape of the average diameter of 210 mm with the initial permeability of around 10000. The sensitivity and time constant of the electronics system attached to the permalloy core, can be varied according to the beam conditioning. The typical sensitivity and the time constant are 0.2 microampere and 5 seconds, respectively.

The travelling wave monitor is placed at the straight section, S5 just upstream the permalloy core monitor. This is used for the detection of Schottky signals from the circulating beam. The structure of inner conductor is a helical type, of which the pitch is adjusted to equal to the beam velocity. The coherent beam signals from the bunched beam, such as the synchrotron oscillation frequency, can be detected with this monitor. The sensitivity for the coasting beam is around 1 microampere at a window frequency of 15 MHz with the signal averaging by the spectrum analyzer.

The DC beam monitor based on the magnetic modulation method has been constructed. It is placed at the straight section, S5 just behind the travelling wave monitor.

The DC beam monitor comprises the laminated amorphous cores with the average diameter of 230 mm. The record of the sensitivity is 0.5 microamperes at the time constant of low pass filter, 1 second.

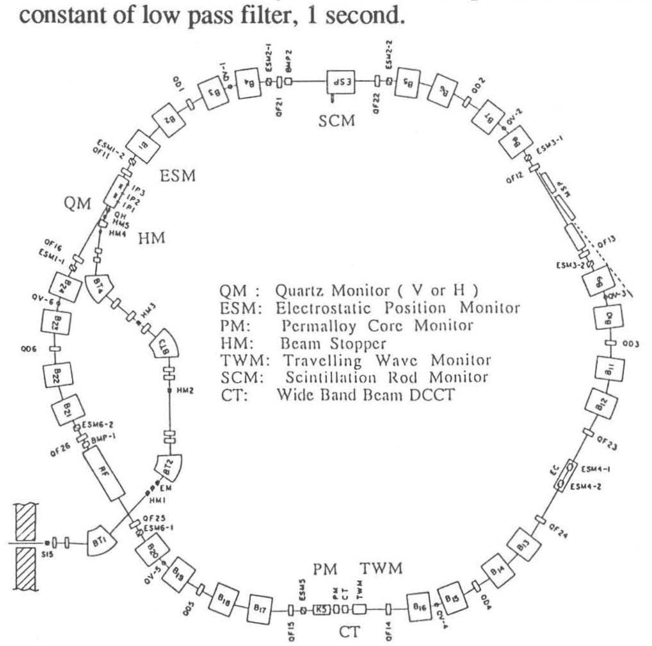

Fig. 1. Layout of beam diagnostic instruments at TARN-II.

To measure the bunched beam positions in horizontal plane, 8 sets of electrostatic monitors are installed at the straight sections, S1 to S6. Each electrostatic monitor comprises a pair of metal plates with a diagonal cut. Details of position monitors are given in the section 3. 2.

3. BEAM DYNAMICS STUDY

3.1 Beam Transport and Multiturn Injection

The ion source of injector cyclotron, is operated under a pulsing mode to increase an output current of the cyclotron. A repetition rate and a pulse width of the output current are 30 Hz and 3 ms, respectively.

The cyclotron and TARN-II is coupled with a beam transport line in 60 m length. A momentum spread and emittance of the injection beam are 0.1 % and 15π (mm.mrad), respectively. Transmission efficiency of the beam was measured as a function of the emittance and distance from the cyclotron. The measured results show that transmission of the 40 MeV α beam of 15π (mm.mrad) is about 45% at an entrance of the ring. The transmission of 13 MeV $^3He^1$ beam of 35π (mm.mrad) was about 15%.

The transported beam is injected into the ring with an electrostatic inflector at the straight section, S1. Optical elements of the ring and transport line, are to be matched to accumulate the beam as much as possible. The injected beam is accumulated into a transverse phase space of the ring by the multiturn injection method. The multiturn injection is performed by using a gradually decreased bump orbit generated by two pulse magnets at the straight sections, S2 and S6. The horizontal acceptance of the ring is designed to be 300π(mm.mrad). The maximum number of multiturn injection is then estimated at 17 turns.

3.2 Closed Orbit Measurement

The horizontal closed orbit around the ring, was measured with use of eight Δ–type electrostatic pickups, each connected by the head-and post-amplifiers. The capacitance between the inner pickup and the earth cover, is measured at typically 65 pF within the deviation of ±2%. The head amplifier, gain of 20 dB, is a low noise type and the measured noise level is as low as 1.7 nV/ √Hz. The amplified beam signals from right (R) and left (L) pickups are sent to a control room and analyzed with two spectrum analyzers of averaging fuction. The beam position are obtained by the relation, $\Delta R = K\cdot(V_R - V_L)/(V_R + V_L)$ where K is a constant determined by test bench experiments. A typical example of closed orbit is shown in Fig. 2 where the deviations of a closed orbit distortion (COD) are around ten mm's.

The correction of COD is performed using six correction coils, each wound on a bending magnet in a sextunt in the ring. The current in each correction coil is calculated so that the COD is to be minimized.

Machine parameters, such as the transition γ, local dispersion functions η, can be experimentally obtained by the closed orbit shift (ΔR) versus RF frequency (Δf) and the field strength of bending magnet (B). The measured values

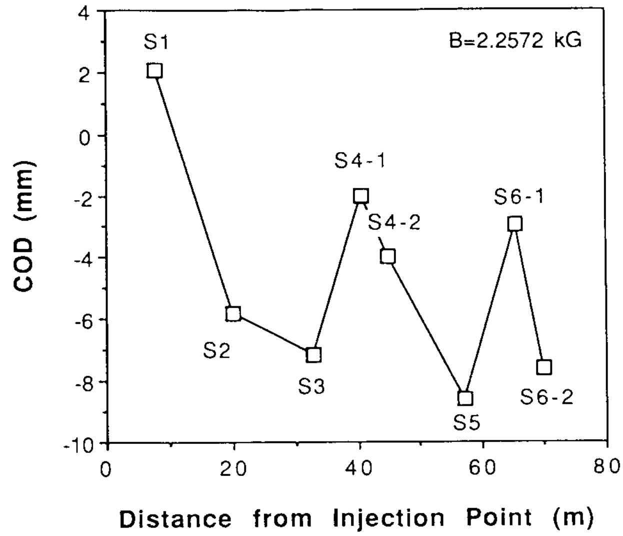

Fig. 2. Closed orbit distortion around the ring.

of ΔR/Δf and ΔR/ΔB are typically 5.62 (mm / kHz) and -2.70 (mm / Gauss), respectively which are around 20 % different from the calculated values by the computer code "MAGIC".

The vertical COD's are not yet measured. The COD calculation with MAD program shows that the maximum COD would be as large as 15 mm due to the rotation of bending magnets and the deviation of central axis of Q magnets. Therefore the vertical correction coils are prepared and the measuring system for vertical COD are now being constructed to improve the vertical ring acceptance.

3.3 Chromaticity Measurement

The horizontal and vertical betatron tunes ν_x, ν_y were measured as a function of beam momentum, and they were corrected with use of a sextupole magnet located just downstream a focusing quadrupole magnet at the straight section No. 5. The experimental procedure was as follows;

Injected beam was firstly captured by the RF field and was accelerated up to the required beam momentum, holding the magnetic field constant. Then the tune values were measured with the RF knockout method. The maximum fractional momentum variation Δp/p was around 1 %, corresponding to the horizontal movement of beam position 44.8 mm when the RF frequency was varied from 1.117 to 1.125 MHz. A current of sextupole magnet was adjusted to correct the horizontal tune values. In Fig. 3, the measured results are given as a function of fractional momentum change Δp/p. The horizontal tune ν_x is constant, chromaticity corrected, in the case that the current of sextupole magnet is 35A. On the other hand, the natural chromaticities, $\xi = (\Delta\nu/\nu)/(\Delta p/p)$ at Isextupole = 0, were measured at $\xi_x = -1.83$ and $\xi_y = 2.13$, respectively.

3.4 Beam Transfer Function

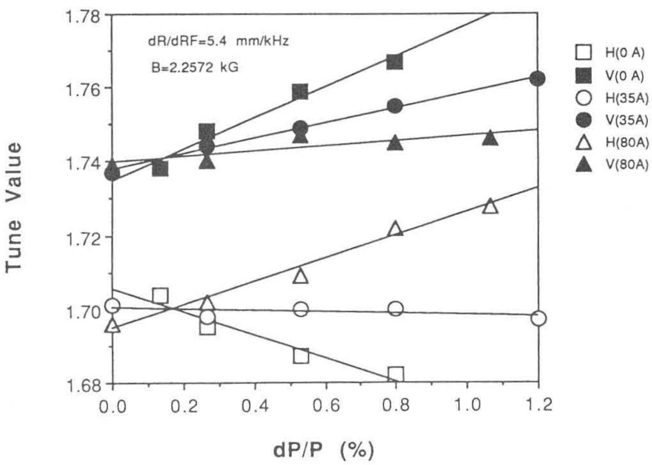

Fig. 3. Horizontal and vertical tunes vs. beam momentum.

A tracking generator, an analog spectrum analyzer, transverse and longitudinal Schottky signal detectors, a wideband power amplifier with the max. power of 60 watt, and a kicker are used for the measurement of beam transfer function. The kicker is composed of two sets of parallel plates, one is for the horizontal and the other for the vertical. The RF signals from the tracking generator are amplified and fed to the kicker. The longitudinal or transverse Schottky signals are detected by the electrostatic pickup, 1/6 circumference downstream the kicker. Schottky signals are observed on the spectrum analyzer with co-use of tracking generator. The strong signals are corresponding to coherent longitudinal beam oscillations, integer times the revolution frequency, whereas the non-coherent signals, two side band signals neighbouring the coherent signals, could be observed. They represents the betatron motions with the frequencies given by the following relation;

$$\omega_{x,y} = (m \pm \nu_{x,y}) \, \omega_{rev} \, ,$$

where m is an integer and ω_{rev} is a revolution frequency around the ring. Thus the precise values of betatron tunes

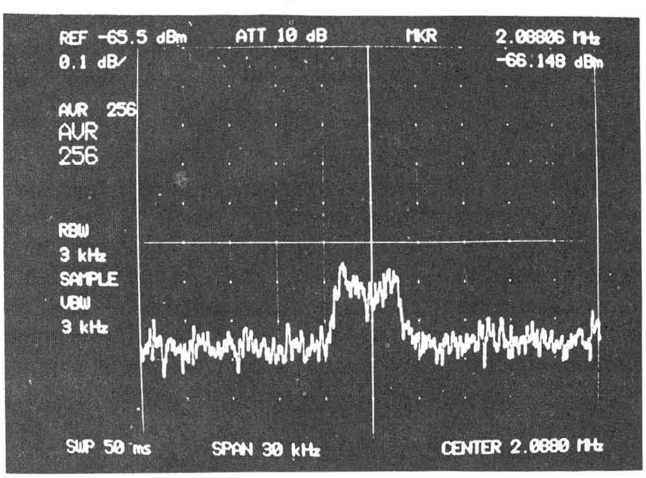

Fig. 4. Schottky signals of betatron sideband.

can be determined by the BTF measurement instead of RF knockout method. The observed ω_x has a finite spread as in Fig. 4 where the width of frequency Δf is 4.3 kHz, corresponding to m=2 and ν_x=1.7487, respectively . Normally this spread is due to the momentum spread of circulating beam and to the finite chromaticity , and is represented by the following formulation;

$$\Delta\omega_x = (\xi_x + (m \pm \nu_x) \, \eta) \cdot \Delta p/p \cdot \omega_{rev} \, ,$$

where η is the dipersion function defined by $\eta = \gamma^{-2} - \gamma_t^{-2}$.

The closer observation shows that the shape of the frequency spreads of sideband, has two peaks. The separation of two peaks becomes smaller when the RF voltage is put off. The analysis of these phenomena is now in progress.

3.5 Beam Life Time

The life time of the stored beam is determined by several factors in the cooler ring. The life of the heavy ions with atomic electrons, is determined by the rate of electron capture at e-cool section. For the molecules, such as H_2^+ or H_3^+, the dissociation due to the residual gas, play a key role. For the completely stripped light and heavy ions, the multiple scattering with residual gas in the vacuum chamber, is a leading factor. In any cases, the operation points, ν_x and ν_y values, should be selected so as to avoid the resonance lines, at least up to 5th orders. Otherwise beam would be lost due to the emittance growth by the resonance effects.

Here the experimental results of 40 MeV α beam, are explained . The average vacuum pressure at TARN II ring is presently ~ 2×10^{-10} Torr, measured by the B-A gauges. The beam currents are measured by the parmalloy core monitors. We measured the e-folding beam life time for two cases, the one the RF voltage of 500 Volt was applied and the other the RF was put off. In the former case, the life time was 100 seconds whereas it was 400 seconds in the latter case. Short life time in the presence of RF field, could be explained by the following considerations; The betatron operation points extended over the resonance lines due to the finite chromaticity and large momentum spread with the phase oscillations . In the present case, the tune spreads $\Delta\nu$ are evaluated at ~ 3×10^{-2} and then the operation lines did cross or touch the stop band of resonance lines of 5th orders. Precise chromaticity corrections of both the horizontal and vertical directions, would be necessary to obtain the long life time in the presence of RF field.

Another example is the ionization energy loss of the circulating beam due to the collision with residual gas. The 40 MeV α beam was stored in the ring and Schottky signals was observed. The shift of the central frequency of the spectrum, 360 seconds after the beam injection, was Δf = 7.5 kHz at the 35th harmonics of revolution frequency (Fig. 5), which corresponds to the energy loss of 44 keV and the horizontal beam position movement of 2 mm.

By using the data of residual gas analysis and this ionization loss, the average vacuum pressure, N_2 equivalent, was determined 7×10^{-11}, roughly two times better than the value obtained by B-A gauges.

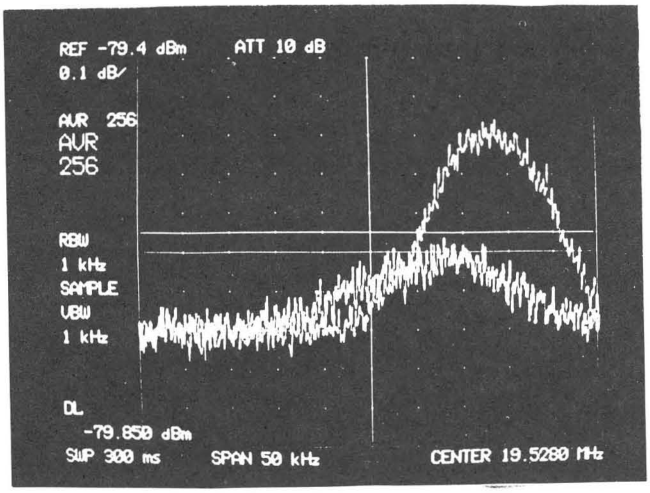

Fig. 5. Longitudinal Schottky signals at the injection and at 360 sec after the injection.

4. ACCELERATION

The synchrotron acceleration system was completed to the designed maximum energy 370 MeV/u for light ions. However, due to the limitation of the electric power station in the campus, the presently available energy is 220 MeV/u. The detailed descriptions of the RF system are given elsewhere[3], and in this chapter, two subjects concerning the RF acceleration are presented.

4.1 Tracking Error Correction

Four magnet power supplies, one for bending magnet and 3 for Q magnets, should be excited synchronously with a finite tracking error. From the experiences at DC operation of the ring, the permissible tracking error was estimated at 0.2 %. For this purpose, the self learning correction system for tracking error was built with a microcomputer system, PSC 1000, consisting 5 sets of computer boards and I/O interface boards.

At each power supply, Digital to Analog (DA) and Analog to Digital (AD) converters are equipped for the current control. The 1st approximation pattern data, caculated from the ideal reference pattern data, are sent firstly to each power supply via DA converter, then the excitation currents of power supplies are measured with DC current transformer. Then the measured results are compared with a reference ideal value. At this first trial, the tracking error was as much as 5% due to the non-linearity and delay of the circuits. The 2nd approximation data, is then corrected to advance the readout time for the compensation of delay components. Afterthat the self-learning correction is performed to correct the nonlinear term.

Iteration of the self-learning was finished after 6 or 7 repeating this procedure. The tracking errors between , one dipole magnet and three quadrupole magnets, were finally obtained within 0.2%.

4.2 Beam Acceleration

The beam acceleration is performed by the following procedures: The injected beam is captured adiabatically by the RF bucket within the period 6 ms. In this period, the capture frequency is controlled by a fixed frequency generator to track the twice of revolution frequency of the injected beam. After the adiabatic capture process, the bucket which is controlled by a phase locked loop, takes over the captured beam. The frequency of voltage controlled oscillator, a part of phase locked loop, is regulated by a B-dot generator, position and phase feedback system. The voltage at an acceleration gap of RF cavity is controlled by a AGC system during the whole acceleration period. For example, the injected 10 MeV/u α beam was accelerated up to 220 MeV/u. The field excitation and beam position signals are given in Fig. 6. During the acceleration, the beam position was kept almost constant in the ring. The dB/dt is chosen at 0.37 Tesla/sec.

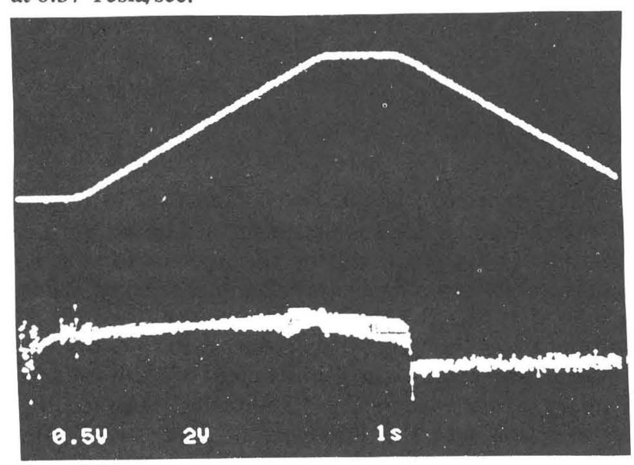

Fig. 6. Excitation pattern of magnetic field and the horizontal beam orbit during the acceleration.

5. ACKNOWLEDGEMENT

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