Beam Acceleration at Cooler Synchrotron TARN II

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Abstract

Light ions were accelerated from 10 MeV/u to 220 MeV/u without any beam loss at cooler-synchrotron TARN II. Two beam-feedback loops, horizontal position and phase, played a key role to attain the successful operation. The circulating beam current was as low as several micro amperes and then the noise reduction in the beam monitors was an crucial issue.

1. INTRODUCTION

TARN II is a cooler-synchrotron being operated since 1989 at the Institute for Nuclear Study, Univ. of Tokyo[1]. It has a function of beam acceleration up to the maximum rigidity of 5.8 Tesla.m as well as an electron beam cooling. The injector is a sector focussed cyclotron with K number 68 which can accelerate a variety of ion beams supplied by ECR ion source. The RF system of TARN II should have the following specifications .

Table 1
RF accelerating parameters

Injection Energy	> 2.58 MeV/u
Acceleration Energy	< 1.1 GeV
Momentum spread at injection	< ±0.5%
Revolution Frequency	0.31 ~ 3.75 MHz
Harmonic number	2
Acceleration Frequency	0.62 ~ 7.50 MHz
Maximum RF accelerating voltage	2 kV

The lowest injection energy is 2.58 MeV/u of $^{20}Ne^{4+}$ ions among 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 3.75 MHz, thus the ratio of the lowest to the highest frequencies is thirteen. The harmonic number is 2 and the RF frequency should cover the range from 0.62 MHz to 7.50 MHz. An acceleration voltage of 2 kV is enough for the beam with 0.5 % momentum spread within the acceleration period of 3.5 sec.

2. ACCELERATION HARDWARE

2.1 Accelerating Cavity

An RF cavity is a single-gap structure which consists of two ferrite-loaded quarter-wave coaxial resonators[2]. In order to produce an accelerating voltage at the gap, a push-pull mode excitation of two resonators is achieved by the help of a "figure of eight" configuration of ferrite-bias windings. Choice of a ferrite material with high incremental permeability is important to realize a cavity with a wide frequency range. We selected a ferrite material, TDK SY-6. The initial permeabilities of 48 ferrite rings distribute from 969 to 1214 and the average is 1093. These 48 rings were alternately stacked in the two resonators according to the order of the permiability to balance two resonators electrically. Measurements of the cavity show that a resonance frequency changes by a factor of 15.5 from 0.59 MHz to 9.18 MHz when a bias field changes from 0 AT/m to 2.59 kAT/m. The lowest value of the shunt impedance is obtained at 250 Ω at around 5 MHz. The final power amplifier consists of a tetrode, RS 2012 CJ of Siemens, which is capable of an anode dissipation of 18 kW. Typical operation parameters of the tube are; anode dc is 4.7 kV, screen grid 1.2 kV and control grid -100 V, and filament 7.2 V, 80 A, respectively.

2.2 Low level RF Electronics System

The low-level rf electronics system is composed of a voltage-controlled oscillator (VCO) and several feedback loops[3] (Fig. 1). Three memory modules store the ramp data: frequency, acceleration voltage, and bias current as functions of bending-magnet field strength. At every 1-gauss increment, measured at the 25th dipole magnet, the data are read from memories and converted into analog voltages through digital-to-analog converters (DACs). The data are fed

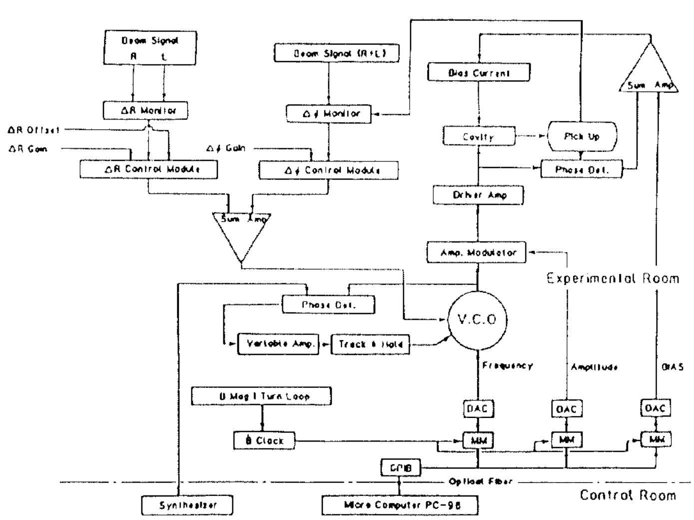

Fig. 1 Block diagram of RF acceleration system

into a VCO, amplitude modulator, and bias current power supply, respectively. The error of bias current or equivalently the degree of cavity detuning, is detected as the phase difference between the rf signals at the grid and plate of the final power tube. It is used for the correction of resonance frequency of cavity via a hardware feedback loops(AFC). In addition, the signals of horizontal beam position(ΔR) and of the phase error($\Delta\phi$) between beam bunch and acceleration RF field, are fed back to the VCO for the correction of RF frequency. The radial feedback loop has a frequency response as $g_r(s) = K_r \frac{1 + T_r s}{s}$, the proportional-and-integration type, where s = jω and T_r is chosen as the inverse of synchrotron angular frequency (~ 1 kHz) at the injection energy. On the other hand, the phase loop is a proportional type. Gains of two closed loops can be varied finely and additionally the offset value can be applied to ΔR controller to adjust the beam orbit during the acceleration. The output RF signal of this oscillator is fed to the driver-and power- amplifiers.

During the injection period the VCO is phase-locked with the rf signal from a frequency synthesizer. The frequency and voltage in the injection period are finely adjusted for maximum capture efficiency. A track-and-hold circuit is inserted in this phase-locking loop to prevent the abrupt variation of VCO frequency at the timing of change from synthesizer-locking to beam-locking. In Figure 2, the timing chart of the RF system is shown. Triggering off the master pulse, the excitation of bending-and quadruple magnets, $d\mathbf{B}/dt$-clock, feedback control gates, and other timing signals, are generated with the proper delays.

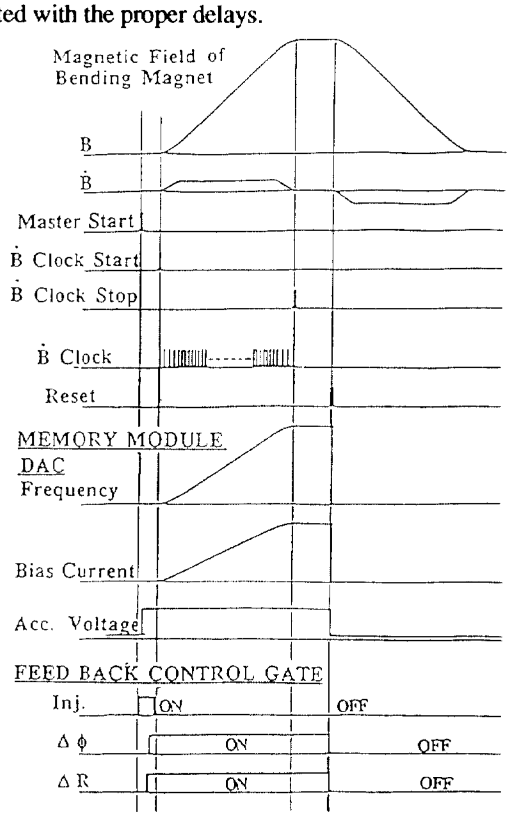

Fig. 2 Timing chart of low level RF system

2.3 Beam Monitoring System

Pick-up electrodes are consisted of cupper plates of standard Δ-shape which are cut diagonally. Side plates are removed to diminish the noise due to beam hitting on the electrodes. The length of pick-up is 194 mm and the aperture is 148 mm wide and 46 mm high. The measured capacitance is around 130 pF.

The detected beam bunch signals are amplified firstly by a wide band amplifier of an FET impedance conversion type from an input impedance 100 kΩ to an output impedance 50 kΩ. The gain can be selected as -10 dB or 20 dB A second booster amplifier has a gain of 0 dB or 40 dB.

The beam signal is further amplified by a double heterodyne module whose gain is selectable between 10 dB and 60 dB by 10 dB step. In this module the input beam signal is mixed firstly with a signal of (50 + f_{rf}) MHz in a DBM (Double Balanced Mixer). A fixed frequency (50 MHz) signals are obtained from this module which contains the informations of amplitude and phase of beam signals. In the final processor, a 455 kHz signals have been made with the above described 50 MHz beam signals and a 49.545 MHz signals from a synthesizer with again a DBM and a low pass filter of 5 kHz bandwidth.

The phase informations, cos ϕ or sin ϕ, and the position dependent signals, right (R) or left (L) , are obtained in the final processor where deviations of closed orbits are derived with the formula ΔX=const.*(R-L)/(R+L)[4].

3. FEEDBACK PERFORMANCES

The characteristics of beam feedback loops, are represented by two block diagrams in Figs. 3 and 4, where the internal model describes the Laplace transformed phase equations with variables $\Delta E(=E-E_s)$ and $\Delta\phi(=\phi-\phi_s)$. Fig. 4 shows the total feedback loops where a Function Generator produces a pattern wave Vpr+ΔVpr, Vpr being the ideal voltage, ΔVpr the error voltage, Vr is a ΔR feedback voltage, Vp is a $\Delta\phi$ feedback voltage, ω_{ideal} equals to G_0.Vpr with the constant G_0 [=$6\pi \times 10^5$ rad/volt/sec] of VCO.

Nr represents a normalizer of radialloop [=65 volt/m], and gr means the proportional-integrator type circuit. Gd means the constant of phase detector [=13.5/π volt/rad] times the proportional type circuit.

The deviation of closed orbit due to the error of RF frequency $\Delta R/\Delta\Omega$rf , is largely suppressed by the proper selection of gains of two loops. As a typical example, in Fig. 5, the calculated values of Fourier components of closed orbit deviation are given as a parameter of ΔR gain. The upper two curves are in the case of no radial feedback, whereas the lower twos are corresponding to Kr=0.005. Peaks in the curves are due to synchrotron frequencies. It is clearly shown that the ΔR loop works in the low frequency region, up to around 1 kHz and hence the band width of integrator type circuit should extend to this value. Details of analysis of feedback loops in the RF acceleration will be published elsewhere[5].

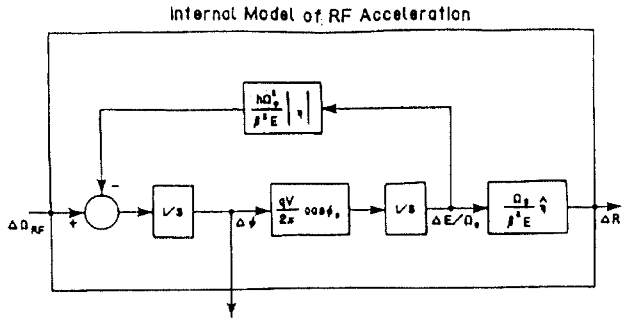

Fig. 3 Laplace transformed model of phase equations

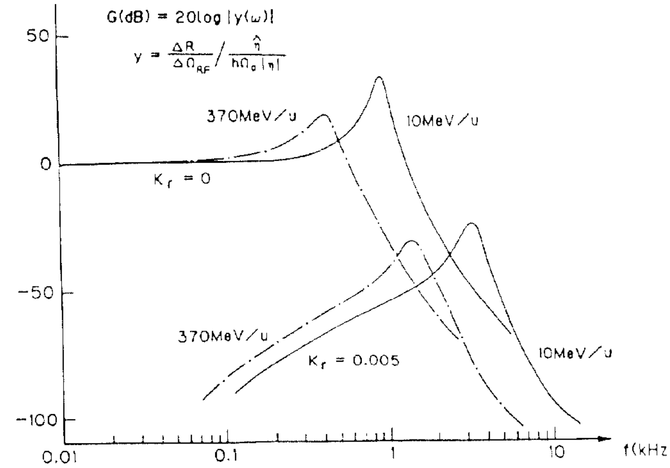

Fig. 5 Transfer functions of radial feedback closed loop

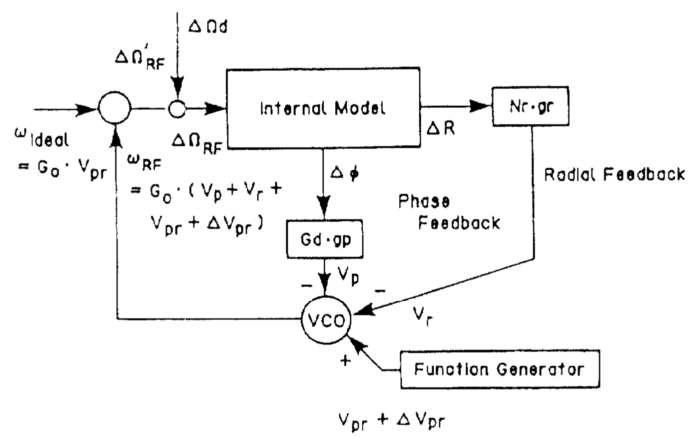

Fig. 4 Feedback diagram

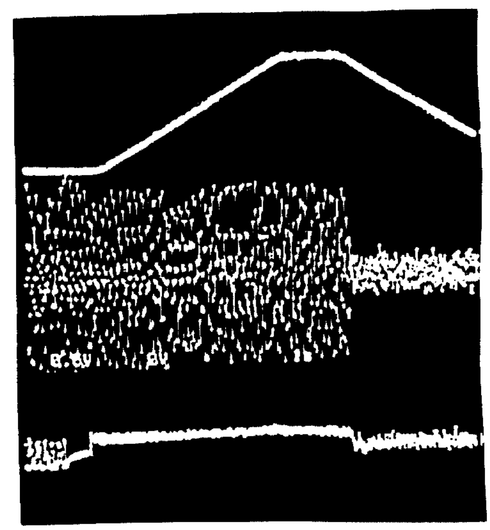

Fig. 6 B-pattern, circulating current and ΔR signals

4. EXPERIMENTAL RESULTS

Typical examples of α beam acceleration from 10 MeV/u to 220 MeV/u is illustrated in Fig. 6 where the B pattern (upper), 2.3 kG at the bottom and 11.2 kG at the top, and the circulating current (middle), around 10 micro ampere and ΔR signals are given where we can find that the deviation of closed orbit from the central orbit is controlled within several mm. We adjusted the bandwidth of two loops and found that the stable acceleration was performed for the ΔR bandwidth of 200 Hz, whereas the Δϕ bandwidth should be extended at least up to 5 kHz for the stable acceleration.

Another important issues are the tracking of Q magnet currents with bending magnet current. There are three groups of Q magnets and each current during the acceleration, are controlled with self-learning procedure to attain the tracking error within + 0.2%. The operation points (Qx, Qy) , is chosen as 1.705 and 1.732 which is enough far from the 3rd order resonances even when the Q magnets tracking error are varied 1%.

Presently the maximum energy is limited due to the capacity of central electric station at the Institute.

5. ACKOWLEDGEMENT

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