CONTROL OF RF ACCELERATION SYSTEM FOR TARN II

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ABSTRACT

In order to clarify a guiding principle in a design of control and regulation of rf acceleration system for a heavy-ion synchrotron, TARN II at INS, the following subjects are considered: operation process, causes of beam losses, and information from beam signals. A scheme of control and regulation of the rf system is proposed.

INTRODUCTION

A heavy-ion synchrotron, TARN II at INS[1], is capable of variable particles and variable energy. A wide mass range from protons to Ar can be accelerated. The maximum energy is 1.3 GeV/nucleon for ions with unity in a charge to mass ratio, 450 MeV/nucleon with a half, and so on. Because the transition energy of the TARN II is designed at 810 MeV/nucleon, only protons are accelerated to the energy of 1.3 GeV being over it. The requirements for rf acceleration system are the frequency range of 0.77 - 7.5 MHz and the maximum rf acceleration voltage of 6 kV.

Because beam parameter such as injection energy, acceleration energy, a charge to mass ratio of ions, momentum spread and intensity varies widely depending on ion species, accelerator parameter such as radio frequency, rf amplitude and rf phase of rf acceleration system must be widely changed. In this respect, it is desired that control and regulation of the rf system provide the correct relation between the both parameter quickly and reliably.

OPERATION PROCESS OF TARN II

The TARN II works repeatedly in the following process: multi-turn injection under fixed strength of a magnetic field, capture under the same field, rf acceleration at an increase in the field, fast or slow extraction under fixed strength of the field. A field change is made in a constant increase of an exciting current for magnets.

As a result of multi-turn injection, a coasting beam is formed. Amplitude of an rf voltage is then raised in parabolic fashion of time in order to capture the beam by adiabatic trapping. In the latter half of the capture period, beam bunches are formed.

The beam bunches always hold during an acceleration period. Parameter of the rf system is controlled to satisfy two kinds of conditions at the same time. One is the acceleration condition corresponding to the increase in the magnetic field. The other is the rf-bucket area condition in which the area should be somewhat larger than a longitudinal phase space area of the bunched beam in order to avoid a beam loss. Consequently, in the initial period of acceleration, momentum spread once becomes wider compared with that of the captured beam. It is then improved with an increase in energy through acceleration. In the final period of acceleration, the rf amplitude is chosen in different values depending on extraction methods.

In a case of fast extraction, the beam bunches are necessarily kept under relatively large amplitude of the rf voltage: a distance between the bunches is used for a fast rise of kicker magnets. The rf voltage is applied until the beam is completely kicked out from the ring. In a case of slow extraction, a coasting beam is formed by adiabatic process which is just the reverse of injection, capture and acceleration. Therefore, during the slow extaction period, the rf voltage is completely removed although the beam is circulating in the ring.

It should be noted that no beam signal is measured by beam monitors for the bunched beam during the injection, the early capture and the slow extraction because of the coasting beam.

CAUSES OF BEAM LOSSES FROM RF-SYSTEM STANDPOINT

In order to design good system for control and regulation of the rf system, it is helpful to understand causes of beam losses in relation to the rf system. Those are roughly divided into five items: adiabatic and non-adiabatic variations in accelerator parameter in a case of the bunched beam, mistuning of accelerator parameter in a case of the coasting beam, excitation of beam instability, and other mechanisms. Beam losses occur when the beam hits walls of vacuum chambers in deviating its position from the designed orbit of the ring by these causes.

Adiabatic variations

Accelerator parameter such as a magnetic field, radio frequency, rf amplitude and rf phase is controlled by the pre-programmed values as a first step. Because these values are usually different from desired ones for the actual beam circulating in the ring, adiabatic variations of the parameter occur. When the bunched beam is circulating in the ring, the variations except for the magnetic field are compensated by proper feedback loops driven by beam signals.

Ripples in the magnetic field affect an orbit of the beam and consequently affect the beam signals. The feedback loops with a relatively slow response for the adiabatic variations can effectively compensate the ripples in changing other parameter such as radio frequency.

Non-adiabatic variations

Non-adiabatic variations in the accelerator parameter of the rf system come from hum, noise and transients in programs for control and regulation, and in automatic tuning system of an rf cavity. Another apparent transient occurs when the beam is being accelerated through the transition energy by the γ_t-jump method. Therefore, feedback loops for the non-adiabatic variations are necessary.

There are two approaches to construction of such loops. One is a phase locked loop. A beam signal from pick-up electrode is considered to be an rf signal with correct frequency and correct phase. This signal is used for a reference signal of the rf system. The other is made by proper feedback loops with a fast response enough to compensate the non-adiabatic variations. The latter is chosen for the present plan in view of relatively low intensity of the beam.

Mistuning

When a coasting beam is circulating in the ring, no beam signal is observed directly by beam monitors of non-intercepting type. Therefore, it is very difficult to compensate mistuning between accelerator parameter and beam parameter. Most probable occasions are mistuning between injection energy and a strength of the magnetic field during injection period, and between a revolution frequency of ions circulating in the ring and an operating frequency of the rf system during the former period of capture process.

In order to overcome this problem, beam parameter should be known with a high accuracy and then pre-programmed values of accelerator parameter should be evaluated with a high accuracy. Moreover, the entire accelerator system should work reliably to achieve these values with a high accuracy. In this respect, it is important to accumulate operation data for various kinds of ions.

Beam instability

Beam instability usually occurs when the beam intensity is very high, because the instability is deeply related to a space charge effect of the beam. The effect of beam instability seems not to be so serious in the TARN II because of relatively low intensity of heavy-ion beams.

Motion of particles in synchrotrons is expressed by betatron and synchrotron oscillations. Moreover, a group of the particles oscillates as a whole in transverse and longitudinal phase spaces: coherent transverse and longitudinal oscillations. Bunch-shape oscillations are coherent longitudinal ones for the individual beam bunch. They are characterized in modes such as dipole, quadrupole, and so on. Oscillating frequency of each mode is related to integral multiples of the synchrotron frequency: fundamental one for the dipole mode, 2nd harmonics for the quadrupole mode, and so on.

The oscillations are usually excited through interaction between the beam and electromagnetic environment of a synchrotron such as chamber walls, rf cavity when intensity of the beam is high. On the other hand, these are possibly excited in another cause which relates to the synchrotron frequency, ripples in the magnetic field, and feedback loops of the rf system for compensation of radial-position error. This cause seems to be severe when the beam is accelerated through the transition energy, because the synchrotron frequency becomes low near the energy and this results in possible coupling between the bunch-shape oscillations and the ripple. Beam monitors and feedback loops should be designed well not to excite the oscillations.

Other mechanism

One of other mechanism of a beam loss exists at the initial period of acceleration process if the horizontal betatron acceptance is fully used during multi-turn injection. A beam loss is due to an increase of beam size which comes from an increase in momentum spread during early acceleration. Any control and regulation of the rf system cannot reduce the loss. On the contrary, it is desired that the beam lost in the mechanism does not hit beam monitors not to contaminate beam signals for feedback loops.

INFORMATION FROM BEAM SIGNALS

It is considered that what kind of information is obtained from beam signals measured by radial-position monitors and beam-phase monitors.

In the case of adiabatic variations of accelerator parameter such as a magnetic field, radio frequency, rf amplitude and rf phase, a stable particle which steadily moves without synchrotron oscillation can exist. For simplicity, a stationary ditribution of particles in a beam bunch is assumed. In this case, there is no bunch-shape oscillation. The stable particle locates at the center of gravity of the stationary distribution. Other particles move in synchrotron oscillation around the stable particle. Therefore, information obtained from the beam signals corresponds to the motion of the stable particle. On the other hand, motion of the particle has been well known from equations of motion.

If the magnetic field is completely ideal without adiabatic variations, it is known from expressions of the motion of the stable particle that the radial position of the beam and the beam phase are related to deviations in only radio frequency and in only rf amplitude, respectively. The radio frequency is absolutely corrected by the radial-position signals, because the reference orbit of the ring is the absolutely correct position. On the other hand, it should be noted that there is no absolute reference of the beam phase. The beam phase is automatically determined to a value relative to the rf amplitude, and vice versa. As the rf amplitude is actually controlled by the pre-programmed values, the beam-phase signals are not useful from the ponit of view of the expressions of the motion of the stable particle.

Another viewpoint on the beam-phase signal is important. It is essentially an rf signal with correct frequency and correct phase of the beam bunches. Therefore, the signal is useful to correct the operating frequency of the rf system. Now, we have two signals to compensate a deviation of the frequency: the radial-position signal and the beam phase signal.

In order to clarify roles of the two beam signals for feedback loops, adiabatic variations in the magnetic field, namely ripples are taken into account. The radial position of the beam and the beam phase are modulated by the ripples if no feedback loop compensate such modulations. It is known from the expressions of the motion of the stable particle that the radial position and the beam phase are related to deviations in both of radio frequency and the magnetic field, and in both of rf amplitude and the magnetic field, respectively. Here, then, we demand assumptively that the radial position of the beam tunes to the reference orbit of the ring. Accordingly, the only radial-position signals should be used for this demand. Because the operating frequency of the rf system is modulated by the ripples in the magnetic field when a deviation in the radial position is corrected, the beam phase is unavoidably modualted by the ripples, too. This apparent modulation on the beam phase is not accepted from the point of view of coupling between the bunch-shape oscillations and the ripples in the magnetic field. In order to damp the oscillations, the beam-phase signal must be used, because most efficient detection of the oscillation is made by the beam-phase signals. Feedback loops with a fast response is necessary.

The radial-position signals and the beam-phase signals are used for feedback loops with slow and fast responses, respectively. This classification corresponds to the compensation of adiabatic and non-adiabatic variations; that is to say, the radial-position signal are used for feedback loops with a slow response to compensate the adiabatic variation, and the beam-phase signals are used for feedback loops with a fast response to compensate the non-adiabatic variations.

BEAM MONITORS

It is known from the above consideration that the beam monitors required for the TARN II are comparable in the type of parameter and the degree of precision with those for other proton synchrotrons. However, in comparison to proton synchrotrons, intensity of the beam is much reduced usually in heavy-ion synchrotrons like the TARN II. Developement of beam monitors which operate at intensity as low as possible is very important.

Electrostatic position monitor has been successfully developed at TARN, INS[2] in measuring a radial-position of a beam with accuracy better than +-1 mm at beam current of 0.5 euA. Essentials of the success are the use of the dual channel tracking filter and reduction of rf noises. Improved beam monitors of this type will be applied to the TARN II being extended in frequency range.

SCHEME OF CONTROL AND REGULATION OF RF SYSTEM

The acceleration of the beam in the synchrotron is achieved by exact relation between the magnetic field and the rf acceleration voltage. Low-level rf system should provide the correct phase relation between the circulating beam and the acceleration voltage.

When the current of the bunched beam is high, the correct relation is realized by the low-level rf system. If the beam current is not high enough to provide beam signals for the feedback loops, the control of the rf system must be done by the rf system itself.

Taking account of this and the consideration described in the preceding sections, we propose a scheme of control and regulation of the rf acceleration system for the TARN II. Fig. 1 shows the block diagram although there is some ambiguity: for example, a number of beam monitors has not been decided.

Frequency source
The frequency source is a voltage controlled oscillator (VCO) which is driven by a sum of the frequency program, the radial-position signal and the beam-phase signal.

Cavity tuning
In order that the resonant frequency of the rf cavity tunes the driving frequency, the direct current for the ferrite biasing is controlled by a phase difference between plate and grid of the final power tube: the phase is kept at 180°.

Amplitude regulation
The amplitude of the rf accelerating voltage is controlled to always hold the pre-programmed value. Regulation of it is made in compensating a difference between the amplitude of the rf cavity and the pre-programmed value.

Synchronous phase
Synchronous phase itself is not tuned because the rf amplitude has priority over it in the present control scheme. In order to change the phase, the amplitude is suitably changed.

Frequency correction
A fast phase correction and a slow frequency correction are made by the beam-phase signal and by the radial-postion signal, respectively. In order to avoid interference between the two correction loops, a response time of them is restricted by appropriate filter circuits.

Switching at transition energy
There is parameter which should be changed in its value and/or in its sign at the transition energy. Two of such parameter are shown in the figure: the radial-position signal and the beam-phase signal. The frequency program and/or the phase-shift compensation program are also changed.

Phase-shift compensation
It is considered in the present scheme that a reference signal is generated at the voltage controlled oscillator. A phase of the rf voltage at the cavity possibly shifts from that of the reference signal depending on the operating frequency because of characteritcs of electronic circuits. A phase shifter located between the VCO and the cavity compensates it by the pre-programmed value.

DISCUSSION

The scheme proposed in the paper is a conceptual design of control and regulation of the rf system. Details of the programs, electronics and others will be studied continuously.

REFERENCES

1. T. Katayama, TARN II PROJECT, see these proceedings.
2. S. Watanabe et al., POSITION MEASUREMENT OF FAINT BEAM WITH ELECTROSTATIC MONITOR, see these proceedings.

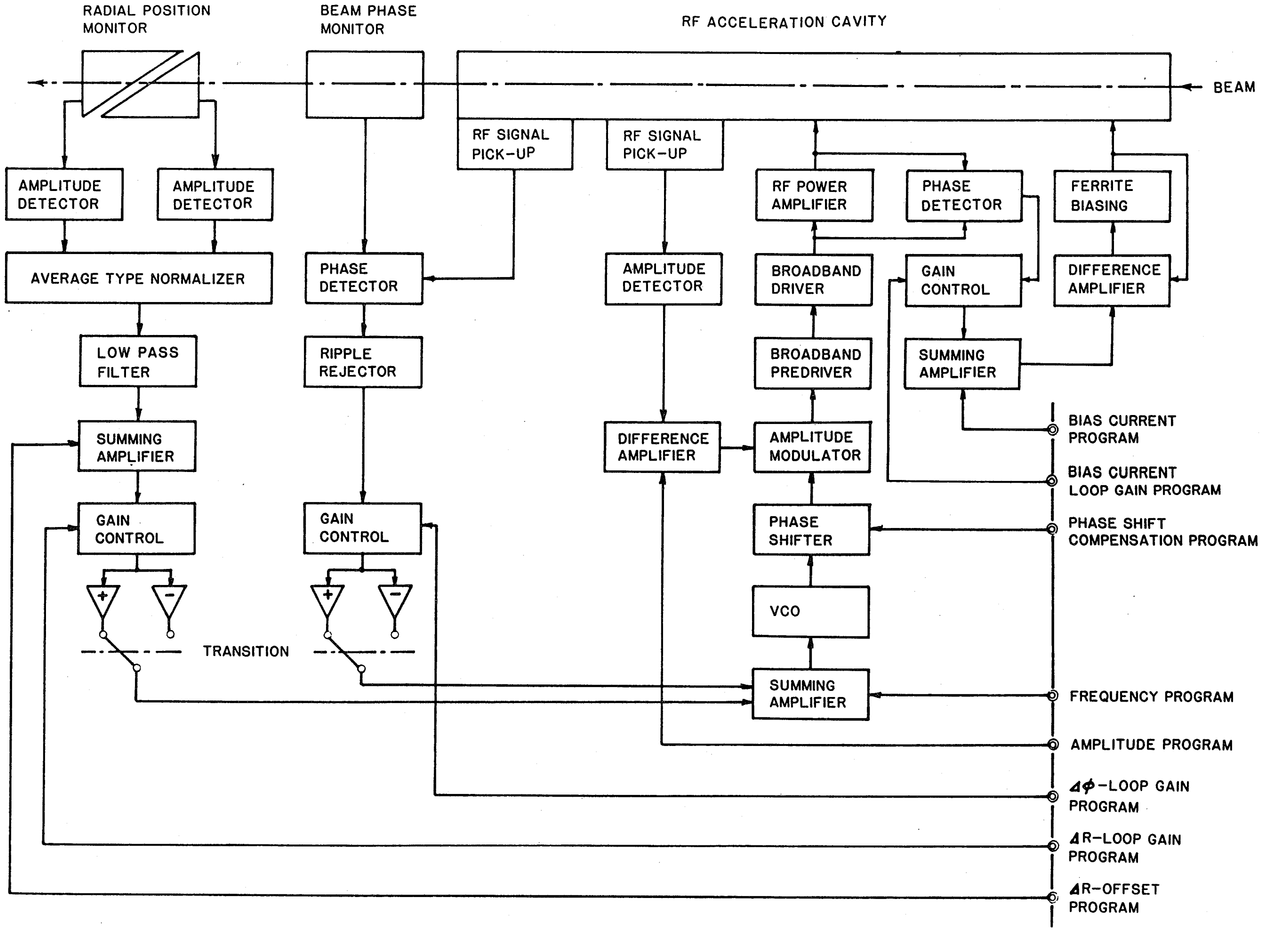

Fig. 1 Block diagram for the control and regulation of the rf acceleration system for TARN II.