The Indiana University Cooler Injector Synchrotron Rf System*

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Abstract

A 2.2 Tesla-meter synchrotron with 17.4 m circumference is being built at the Indiana University Cyclotron Facility (IUCF). The purpose of the project is to achieve higher luminosity for nuclear physics experiments using electron cooled polarized light ion beams in the IUCF Cooler synchrotron. The injection line for the booster synchrotron consists of an RFQ/DTL linear accelerator delivering a 7 MeV proton beam and a 6 MeV deuteron beam for the booster injection. A debunching system will be installed in the injection beamline to reduce the energy spread of beams out of the linear accelerators. Charge-exchange injection is used for high intensity multiturn beam accumulation. The booster output beams, 200 MeV for protons and 105 MeV for deuterons, will be transferred bucket to bucket to the IUCF Cooler synchrotron. The rf system design for the booster synchrotron is presented in this paper.

I. INTRODUCTION

The design of the rf system needs to support the spin-transparent booster synchrotron operation which is described as follows.

The beams from a high intensity polarized ion source are preaccelerated by an industrial RFQ/DTL system to a proton energy of 7 MeV or a deuteron energy of 6 MeV. The beam from the preaccelerator is then debunched to reduce the energy spread. Once the stripping injection beam accumulation is finished, the booster rf system will adiabatically capture the beam in the h=1 bucket. Acceleration follows and lasts about 0.6 sec. Higher cycling rates up to 5 Hz are included in the rf system design for possible future upgrades. At the top energy of the booster synchrotron, the beam phase is aligned with the rf phase of the IUCF Cooler Synchrotron. A fast kicker extracts the beam from the booster for bucket-to-bucket transfer into the Cooler.

The booster is designed to achieve an intensity of 2.5×10^{10} particles. The γ_t of the ring is 1.271 and the synchrotron will operate below γ_t.

II. DEBUNCHING SYSTEM

The beam out of the RFQ/DTL system has a tight time structure with a width < 0.2 ns. The energy spread is significant at $\Delta E/E = \pm 1\%$. Such an energy spread would dilute the longitudinal phase space and exceed the energy acceptance of the IUCF Cooler [1]. A debuncher is therefore designed for the injection beamline to reduce the energy spread.

The debuncher operates at a frequency of 425 MHz, the same frequency of the beam bunches delivered by the RFQ/DTL preaccelerator.

A drift distance of 2 meters is chosen to tilt the beam in the longitudinal phase space --- with the higher momentum particles leading the lower momentum particles linearly in time. With such a short drifting, the beam time spread will be within the linear region of the 425 MHz debunching rf sinusoidal wave and debunching can be highly efficient. However, to match the energy versus time slope of the drifted beam, the debunching cavity must operate at 80 to 100 kV.

Because of the beam velocity and the high rf frequency, the transit factor can drastically lower the voltage the beam sees when crossing the cavity. Two measures are taken to bring the transient factor as close to unity as possible: the debunching cavity rf gap distance is designed at 1 centimeter; the diameter of the beam pipe leading to the gap is also limited to 1 centimeter to concentrate the longitudinal component of the rf field near the rf gap. At 425 MHz, the field strength of such an rf cavity is approximately half the classical Kilpatrick limit. Proper surface processing and good vacuum pumping is important to prevent sparking.

The debunching cavity will be driven by a planar triode amplifier manufactured by the AccSys Technology Inc. About 20 kW of rf power will be delivered to the cavity in 300 μs pulses.

To achieve efficient debunching, it is essential that the debunching cavity rf be precisely phase-locked to the beam.

This will be accomplished by a phase feedback loop controlled by the debunching system's low level rf electronics. Because the cavity time constant is significant compared with the rf pulse width, as indicated by the cavity induced pole in the system transfer function:

$$\frac{1}{s\frac{2Q}{\omega}+1} \quad \textbf{(1)}$$

an appropriate zero will be introduced in the system transfer function to offset the cavity effect.

The debunching cavity rf amplitude is also regulated by a fast feedback loop. A slower, discrete loop will adjust a mechanical plunger inserted in the cavity to correct drift of the cavity resonating frequency.

III. BOOSTER RING RF SYSTEM

During injection, the rf cavity in the booster synchrotron is turned off. The debunched beam, with an energy spread less than ±0.2 %, will coast and increase in intensity due to stripping injection accumulation. When stripping accumulation reaches an equilibrium due to emittance growth, the beam is bumped off the stripping foil and the injection stops. The rf cavity is then turned on, capturing the beam adiabatically with an $h=1$ bucket at the center of beam energy distribution. Computer simulations showed that a linear rf turn-on longer than a couple of synchrotron oscillation periods of the final rf bucket is adiabatic enough to capture almost all the beam [2].

The beam motion inside an rf bucket is inherently undamped, given by the following differential equation for small amplitudes:

$$\ddot{x} + \omega_s^2 x = f(t) \quad \textbf{(2)}$$

where x can be either time or energy error with respect to that of the synchronous particle and $f(t)$ the external driving force.

The driving term on the right hand side of the equation consists of rf parameter and guiding magnetic field fluctuations and causes undamped synchrotron oscillation. The oscillation in the longitudinal phase space is also coupled to the transverse phase space, affecting the radial position of the beam. To provide damping of synchrotron oscillations, the driving term in Eq.2 needs to contain a term proportional to the first time derivative of x.

In practice, the above damping concept is realized by beam feedback control. The error signal caused by synchrotron motion is detected and phase-shifted 90 degrees. The processed error signal is then fed back to the rf cavity with a net differential operation as a part of the rf drive.

Several different approaches are used in modern hadron machines. DC-coupled VCO beam phase feedback with radial compensation [3] is chosen for our system.

In this scheme beam phase is compared with the rf cavity phase. The resulting error is used to drive a VCO that generates the rf cavity signal. Because of the derivative relation between phase and frequency modulations, the VCO introduces a 90 degree phase shift that corresponds to a damping first derivative term of the phase error. Transfer functions of other electronic devices in the feedback path, such as that of the rf cavity, are compensated by introducing classical feedback algorithms at various points of the loop to achieve the necessary overall transfer function.

Such a DC-coupled VCO controlled phase loop is not stable by itself. Because the rf frequency is beam controlled, the beam can accelerate or decelerate itself out of the aperture. An additional radial loop is used to center the beam radially.

It can be shown that for sufficiently large phase loop gain, the response of the phase loop is that of an integrator [3]:

$$\frac{\delta f_b}{\delta f_r} \simeq -\frac{\omega_s^2}{G_p s} \quad \textbf{(3)}$$

where δf_b is the beam frequency change, δf_r the rf frequency change and G_p the total phase loop gain.

The radial loop is realized by measuring the deviation of particles from the ideal closed orbit and using the error to control the VCO frequency. It is equivalent to measuring δf_b since the orbit deviation is caused by beam energy error.

Since the phase loop transfer function is treated as a gain block in the forward path of the radial loop, the overall response is:

$$\frac{\delta f_b}{\delta f_r} = \frac{1}{G_r} \frac{1}{1-\frac{G_p}{G_r \omega_s^2}s} \quad \textbf{(4)}$$

where G_r is the gain of the radial loop with frequency to radial error conversion factor taken into account. The overall transfer function is thus that of a first order low pass response, with a time constant of:

$$\tau_r = \frac{G_p}{G_r \omega_s^2} \quad \textbf{(5)}$$

This time constant can be set much lower than the

synchrotron oscillation frequency ω_s. Rf and guiding magnetic field noise will be heavily filtered. The beam will only move adiabatically at frequencies much slower than ω_s [3].

Eq.5 also shows that with judicial selection of phase and radial loop gains, the beam is essentially self centering in the closed orbit with little error.

Although the cavity impedance is relatively low at the order of 1 kΩ, the overall cavity voltage is also low and the beam intensity induced voltage will significantly affect the rf phase. Fast local feedback around the rf amplifier will be used to compensate the beam loading effect.

IV. SYSTEM IMPLEMENTATION

The rf system will consist of a single ferrite-bias-tuned cavity capable of a wide tuning range, driven by a 300 Watt solid state amplifier and tuned by a 20 Ampere bias supply [4] [5].

The low level signal processing will use an upconverting superheterodyne scheme, with the intermediate frequency (IF) chosen at 10.7 MHz to take advantage of inexpensive consumer FM receiver filters. Preprogrammed local oscillator sweep is chosen for acceleration. A nominal 10.7 MHz VCO will operate within the bandwidth of IF filters to provide precise frequency and phase control.

The beam phase signal will be picked up by the sum signal of a beam position monitor of sufficient bandwidth. The radial error of the beam will be obtained from the averaged difference signals of two beam position monitors half a betatron period apart to compensate closed orbit errors.

Standard analog PID processing techniques will be employed to control rf cavity amplitude and rf tuning. The rf voltage during acceleration will be programmed to provide the correct phase space area for varying synchronous phase angles. The change of synchronous phase angle during acceleration will be adiabatic. This approach makes the control of acceleration synchronous angles extremely simple [6].

Although the rf system frequency and phase controls are beam feedback based, the rf system must also be able to provide precise phase and frequency control with other reference sources. During injection and extraction, the beam phase control must be relinquished to the RFQ/DTL accelerator and the Cooler synchrotron rf. The transition between the reference sources needs to be adiabatic with respect to the beam longitudinal motions.

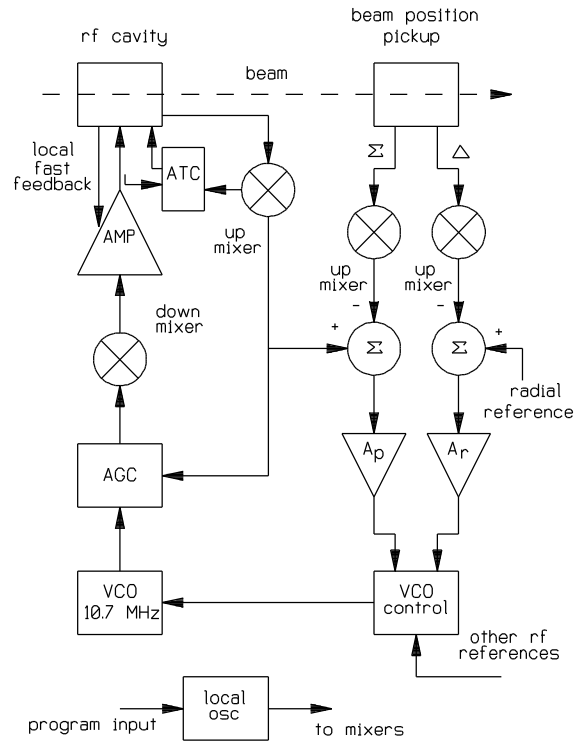Fig.1 is a simplified block diagram of the booster synchrotron rf system.

Figure 1. Principle block diagram of the IUCF CIS rf system.

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VI. REFERENCES

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