The New Booster Synchronization Loop*

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I. INTRODUCTION

The AGS Booster must be synchronized to the AGS rf system before bunch-to-bucket transfer of the beam. The Booster delivers four batches at 7.5 Hz and extraction occurs at full acceleration rate, leaving only 5 ms available for synchronization. An improvement has been made to the synchronization feedback loop. A new loop compensator has been designed using a state variable representation. The three state variables are, beam phase and frequency, and the reference input to the beam control phase loop. The design uses linear quadratic optimum control to achieve greater stability and smaller errors. Lock acquisition, without a transient, is accomplished by a circuit that derives the loop reference from the instantaneous state variable feedback value at loop closing. The reference is brought adiabatically to zero at transfer.

II. DESCRIPTION OF THE LOOP

The synchro system senses the Booster beam phase, with respect to the AGS rf cavity voltage and controls the reference to the Booster phase loop. For 5 ms before beam extraction the radial loop control loop is supplanted by the synchro loop as the beam phase is brought to setpoint for bunch-to-bucket transfer to the AGS. Three challenges confront the synchro system: 1. the Booster is still accelerating at a high rate during the 5 ms in which the synchro operates, 2. the inherent integration in the frequency to phase conversion changes the dynamics of the feedback loop so that the simple proportional feedback used for radial control would not be stable, 3. when the loop is closed the phase is arbitrary so large transients could be imposed on the beam control system, which would cause emittance growth or beam loss.

Number one is overcome by a phase-resolved "moving reference frame" system, implemented with a direct digital synthesizer. The synchronization takes place in the "moving reference frame" where the two machine appear to be at nominally the same frequency. This system is described elsewhere [1,2] and is not part of the improvements discussed herein. The dynamics of the feedback loop are treated differently in the new synchro loop. The conventional lead-lag compensation [3] is replaced with a state variable approach in which an optimal linear quadratic regulator is implemented. By summing proportional feedback on the three relevant state variables of the system a more stable and higher gain solution is obtained. The variables are respectively proportional to the beam phase φ_b, to the phase correction φ_r introduced by the radial loop and to the variations $\delta\omega_b$ of the beam frequency. The technique for achieving lock acquisition without transient has also been changed. The previous technique[1,2] employed an intermediate step in which a frequency loop established a specified beat frequency program before the synchro loop was closed. Experience has shown that the reproducibility of the Booster frequency is good enough that the frequency loop is unnecessary. In the new system the transient is avoided by deriving the reference for the synchro loop dynamically from the instantaneous value of the feedback signal at the time of loop closing. This circuit is described in more detail in section 4. below.

III. STATE-SPACE REPRESENTATION

In a first approximation, delays are neglected. We also suppose that the cavity transfer function is equal to one and that we work in the frequency decade 100 Hz to 1 kHz.

In this case, the transfer function between φ_r and $\delta\omega_b$ is $\frac{\omega_s^2}{s}$, ω_s being the synchrotron frequency. A diagram of the simplified system is given on fig. 1.

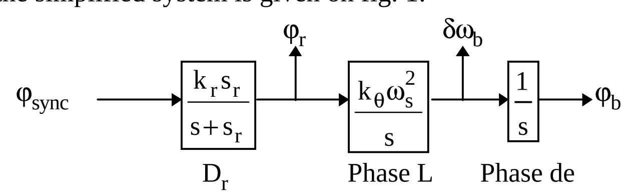

Fig. 1 Simplified schematic

φ_{sync} is the command of the synchro loop, D_r represents the radial loop compensator and k_θ the phase shifter gain. We can deduce a state-space representation. Three variables are sufficient to describe our system.

$$X = \begin{bmatrix} x_1 = \varphi_b \\ x_2 = \dfrac{\varphi_r}{k_r} \\ x_3 = \dfrac{\delta\omega_b}{k_\theta \omega_s^2} \end{bmatrix}$$

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The command is φ_{sync} and we can observe $k_{sync}\varphi_b$, φ_r, $k_\omega\delta\omega_b$, with k_{sync}, and k_ω the detector constants.

The observation vector is therefore $Y=\begin{bmatrix} k_{sync}x_1 \\ k_r x_2 \\ k_\theta\omega_s^2 k_\omega x_3 \end{bmatrix}$.

From the simplified model, it comes out:

$$\begin{cases} \dot{x}_1 = k_\theta\omega_s^2 x_3 \\ \dot{x}_2 = -s_r x_2 + \varphi_{sync} \\ \dot{x}_3 = k_r x_2 \end{cases}.$$

We get the following state-space representation:

$$\begin{cases} \dot{X} = \underbrace{\begin{bmatrix} 0 & 0 & k_\theta\omega_s^2 \\ 0 & -s_r & 0 \\ 0 & k_r & 0 \end{bmatrix}}_{A} X + \underbrace{\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}}_{B}\varphi_{sync} \\ Y = \underbrace{\begin{bmatrix} k_{sync} & 0 & 0 \\ 0 & k_r & 0 \\ 0 & 0 & k_\theta\omega_s^2 k_\omega \end{bmatrix}}_{C} X \end{cases}$$

As the rank of the matrix $\left[B\ AB\ A^2B\right]$ is 3, we can determine a Linear Quadratic Regulator (LQR), with the following performance index:
$J=\frac{1}{2}\int_0^{+\infty}\left(X^TQX+\varphi_{sync}{}^T R\varphi_{sync}\right)dt$, Q minimizing the deviation in states and R the input energy [4]. The Q and R matrices are chosen by the designer to obtain the desired system dynamic.

Calculations are done using Matlab™. The command of the system will be the difference between the reference signal and a linear combination of the three state variables.

IV. LOCK ACQUISITION

The key to the new lock acquisition system is the observation that the Booster beam frequency is very reproducible. It follows then that the Booster phase can be locked to the AGS reference with negligible discontinuity in frequency, less than 200 Hz (< 1 mm of radius). What remains is to eliminate a discontinuity in phase. This is done by using a track-and-hold circuit to acquire the arbitrary value fb of the feedback signal at the time of loop closing. A 360 degree phase detector is used to acquire the phase of the beam. See figure 2. The held value becomes the reference to the synchro loop, so that when the loop closes it is already satisfied and there is no transient. Next, the held value from the track-and-hold (in the hold state) is multiplied via a MDAC with a "ramp-down" function to zero. The reference for the synchro loop is ramped down gradually. The "ramp-down" function is stored in an EPROM and fetched out during the 5 ms period before extraction. Typically a half-cosine function is used because it has zero derivative at the beginning and end, avoiding a frequency transient at the beginning and putting the beam frequency (radius) deviation to zero at extraction.

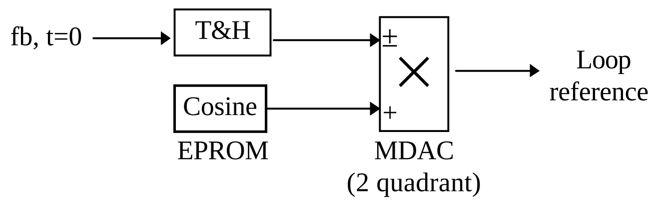

Fig. 2 Lock acquisition system

V. SIMULATIONS

Simulations of the whole system have been performed using the feedback gain values found with the state-space representation described above and with a model including delays and a complete transfer for the phase loop [1]:

$$\frac{\delta\omega_{rf}}{\varphi_r}=\frac{k_\theta\left(s^2+\omega_s^2\right)K\left(\tau'_d s+1\right)\left(s+\frac{1}{\tau'_i}\right)e^{-\tau_d s}}{s\left[\left(s^2+\omega_s^2\right)\left(\frac{s}{s_c}+1\right)+K\left(\tau'_d s+1\right)\left(s+\frac{1}{\tau'_i}\right)e^{-\tau_d s}\right]}$$

In this formula, τ_d is the loop time delay, s_c the cavity response pole, τ'_d and τ'_i parameters of the phase loop compensator and $\delta\omega_{rf}$ the variations of the rf frequency.

The simulation schematic is given on fig. 3.

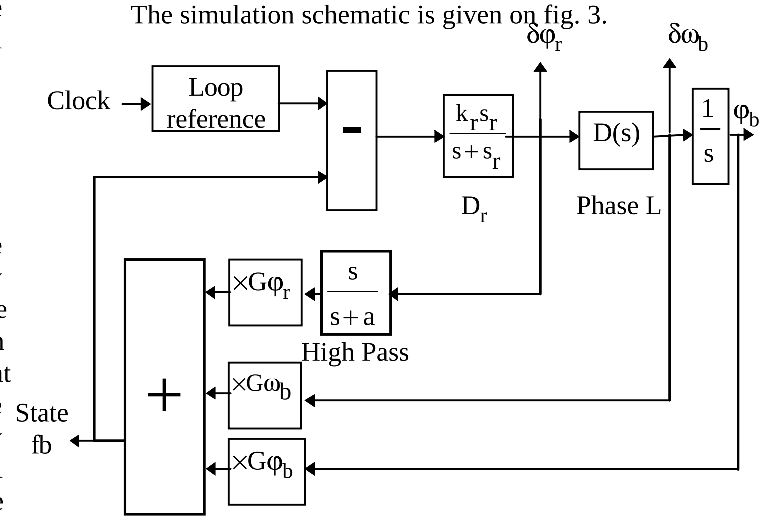

Fig. 3 Simulation schematic

A high pass filter is added on φ_r to cut the DC component. $G\varphi_b$, $G\varphi_r$, $G\omega_b$ are the feedback gains obtainedwith the simplified model, divided respectively by k_{sync}, 1 and k_ω.

The following results have been obtained with:

$$Q = \begin{bmatrix} 10^4 & 0 & 0 \\ 0 & 10^3 & 0 \\ 0 & 0 & 10^3 \end{bmatrix} \text{ and } R = 8000 \text{ for } \omega_s = 1.4\,\text{kHz}.$$

Voltages proportional to the main signals are plotted on fig. 4.

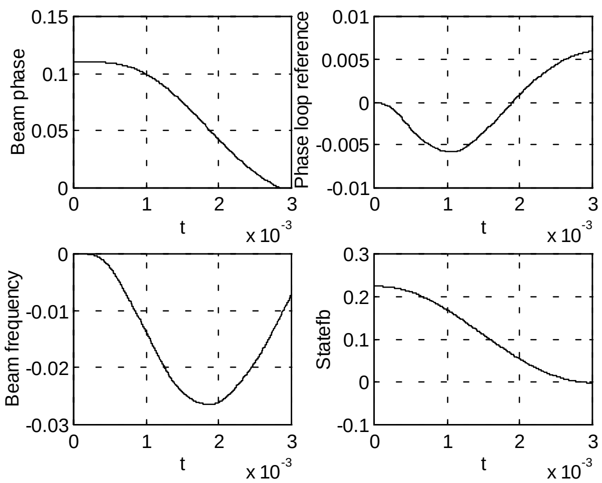

Fig. 4 Simulation results, ω_s = 1.4kHz, φ_{b0} = 0.11 rad, φ_{r0} = -0.011 rad, ω_{b0} = -1.1 Hz.

The phase of the beam follows the cosine function (programmed to go to zero in 3 ms), and, after 3 ms, both the phase and the frequency are equal to zero.

The open loop Bode plot (fig. 5) shows that the system has a 40° phase margin and a 12 dB amplitude margin. The cut off frequency is 1.5 kHz.

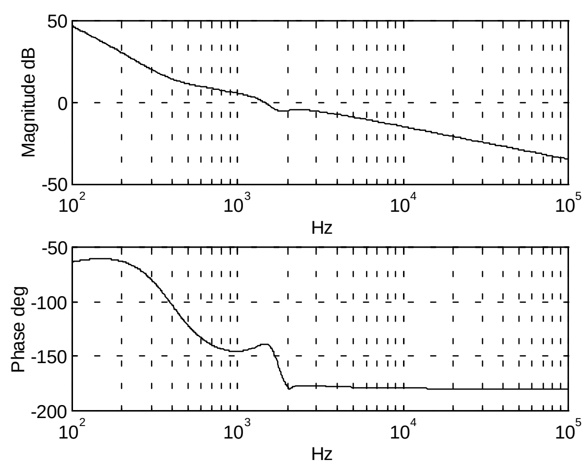

Fig. 5 Open loop, Bode plot

VI. PRACTICAL RESULTS

The three gains in the feedback loop have been realized by using operational amplifiers. The sum of the three channels is subtracted from the reference (cosine function) before being injected back in the system. On fig. 7, the cosine function (top curve) is plotted as well as the synchronous phase for $\omega_s = 1.4$ kHz (bottom curve). The cosine function has been programmed here to go to zero in 3ms. After being held up during 1 ms, the phase goes to zero like its reference in 3 ms and is then held to zero until extraction.

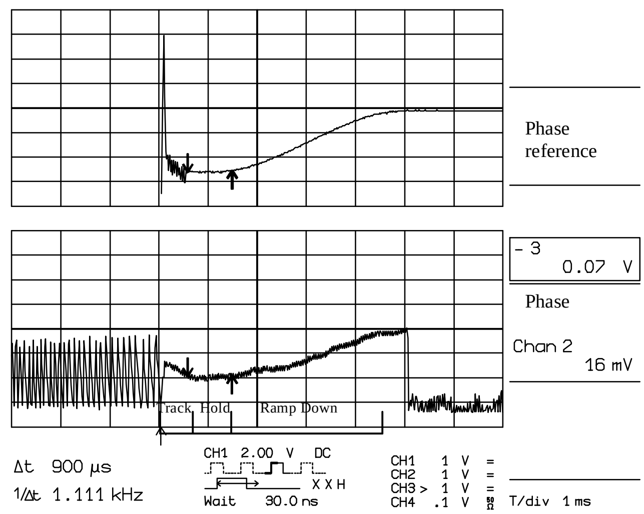

Fig. 6 Synchronous phase measurements

CONCLUSION

The new synchro system allows better synchronization of the Booster bunches to the AGS buckets before transfer between the two machines. State variable feedback and linear quadratic regulator optimization provide good stability margins, high gain, and small transients on the beam. The system has been successfully in operation for all four months on the 1995 high energy physics proton run.

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