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The CODD synchronization system

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Abstract

With the recent re-appearance of Pb ions in the PS, some shortcomings of the CODD synchronization system came to light. This note describes the behaviour of the current system, the problems encountered with ion beams and a solution to these problems.

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Introduction

The CODD synchronization system produces a reference signal at the bunch frequency F_{RF} that follows the bunch during acceleration. Its principle is that of a phase locked loop (PLL), virtually identical in its architecture to that of the PS beam control system [ref]. Its purpose is to provide a timing reference for the trajectory acquisition system.

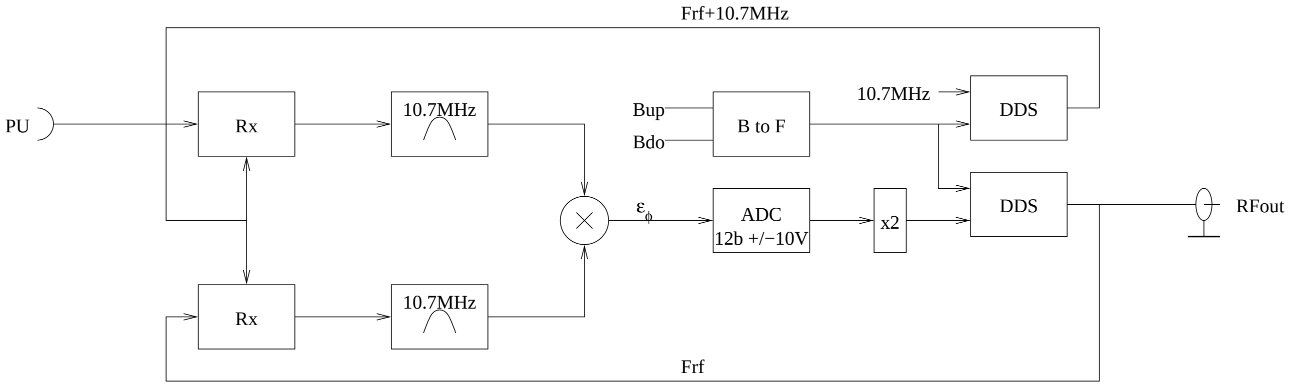

Fig 1: Principle of synchronization loop

Referring to Fig 1, a PU signal is mixed with a frequency nominally at F_{RF}+10.7 MHz and the 10.7 MHz difference is filtered using commonly available ceramic filters. In parallel, the reconstructed F_{RF} is subjected to the same treatment, and the two identically filtered signals are then compared in phase. The phase error, ε_ϕ, is digitized to 12 bits and used to correct the frequency of the DDS signal generator running at F_{RF}. Thus, the reconstructed F_{RF} is phase-locked to the beam signal seen through the PU.

Both DDSs receive as initial frequency setting a value from the B-to-F converter, which calculates an approximation of the bunch frequency, based on the measured magnetic field of the bending magnets, to a relative error of about 10^{-4}. The loop contributes only a very small correction and consequently its adjustment authority is limited to about ±600 Hz.

From the above figure, we can derive a block diagram modelling the dynamics of the loop as a linear time-invariant continuous-time feedback system (Fig 2). Even though part of the loop is implemented as digital logic, this approach is justified by the fact that the dynamics of the loop are much slower than the sampling frequency of the digital part. The ADC runs at 10 MS/s and the DDS at 80 MS/s, while the dominant time constant of the loop is in the millisecond range.

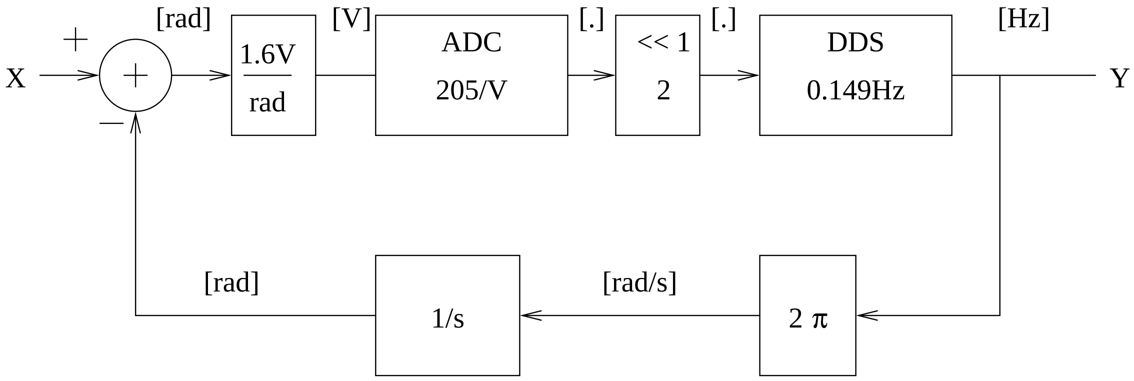

Fig 2: Dynamic model of the loop

The phase detector produces an output of 1.6 V/rad. The ADC has a ±10 V range in 12 bits, yielding a conversion factor of $2^{12}/20=205$ counts/V. The output flat cable of the ADC is shifted by one bit position at its connection to the DDS, accounting for the extra gain of two. The DDS is a Analog Devices AD9955, with a 32-bit phase accumulator, clocked at 80 MHz. The frequency word input has been internally shifted by 3 positions however, yielding an effective conversion rate of 80 MHz/2^{29}=149 mHz/count. The block 2π in the feedback path converts Hz into radians/s. Finally the block 1/s, an integration in the Laplace domain, represents the conversion from frequency into phase. The resulting transfer function, describing the dynamic behaviour of the output frequency as a function of an input phase change, is thus:

$$\frac{Y}{X}=\frac{98\,s}{s+614}$$

From this we derive the response to a step change in the phase error, depicted in Fig 3. As can be seen, the time constant is about 1.6 ms and the frequency error tends to zero.

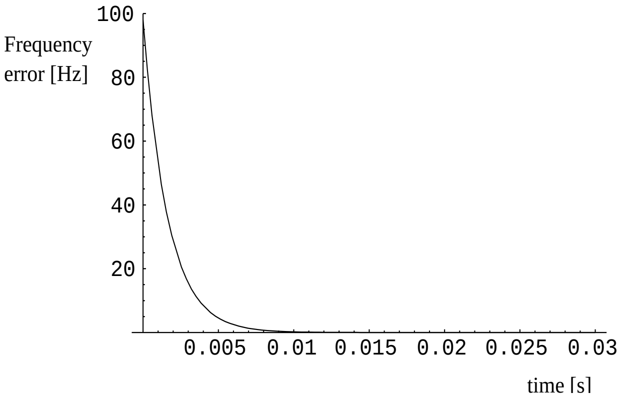

Fig 3: Unit step frequency error response

Problems with ions

All this works well enough when accelerating protons, when the low-level RF (LLRF) system of the PS uses exactly the same B-to-F conversion function as does CODD. However, in the case of PB^{54+} ions, the beam revolution frequency (F_{rev}) at low energy is very sensitive to the field of the bending magnets and it has been found necessary to apply a correction to the B-to-F calculation of the beam control system, using a function generator clocked by the machine millisecond timing (C-timing). This correction can be adjusted at any time, according to the perceived needs of the LLRF specialists. To the autonomous CODD synchronization system, this appears as an external disturbance, summed at a frequency domain node. The equivalent block diagram, re-arranged to represent the dynamic behaviour of the output phase error as a function of an input frequency change, is as shown in Fig 4.

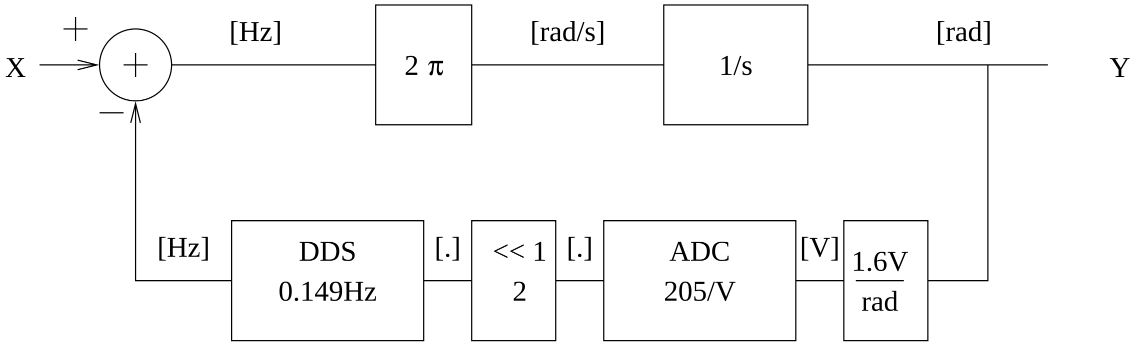

Fig 4: Equivalent dynamics for frequency errors

The corresponding transfer function is now:

$$\frac{Y}{X}=\frac{6.3}{s+614}$$

And the step response is shown below (Fig 5). Evidently, the loop does not fully correct the phase, and a phase error appears that is proportional to the frequency error. A static phase error of some 10 milliradians results for each Hz of frequency discrepancy between the actual F_{RF} and the output of the B-to-F function. The applied corrections are in the 80 Hz ballpark. The resulting phase error is close to one radian! The loop is perilously close to losing lock. The system has indeed been observed to wander widely when accelerating Pb^{54+}.

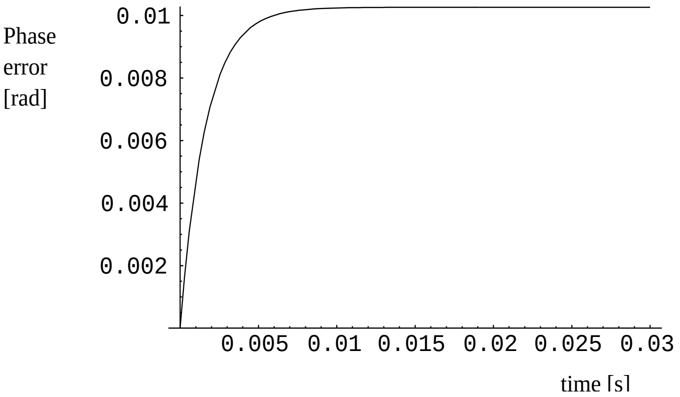

Fig 5: Step response for frequency errors

Even though the CODD system has a freely programmable B-to-F converter, the fact that F_{RF} is now a function of two different domains, the measured B field and the C-timing, is awkward at best. Moreover, any change in the function generator settings or the magnetic cycle would force a recalculation of the whole function, which is implemented as a simple look-up table stored in RAM. This would take about a second each time. Also, the information needed to calculate the function is not easily accessible from the CODD synchronization DSC, since it resides in two other DSCs, one belonging to LLRF and the other to the main bending magnet power supply. Anyway, communication from one DSC to another is frowned upon in the current control system implementation.

It is fortunate that the required correction remains within the ±600 Hz adjustment authority of the loop. A far better solution would therefore be to insert a regulator in the loop that regulates the static phase error to zero, whatever the source of the disturbance. The loop has a node where such a regulator can be inserted easily, between the phase detector output and the ADC input, where the signal is still in the analogue domain. This makes its realization very simple indeed. I chose to insert a PI-regulator with transfer function:

$$H_r = \frac{s\tau_2 + 1}{s\tau_1}$$

The presence of the pole at the origin makes the static phase error tend to nought, while the zero at $1/\tau_2$ affords some control of the dynamic properties of the loop.

So the block diagram after this modification looks like Fig 6:

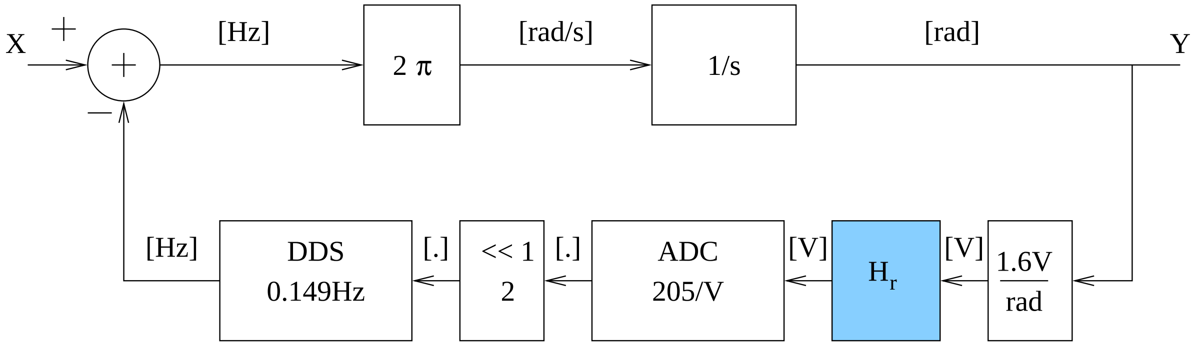

Fig 6: Block diagram with PI regulator inserted

The new system transfer function from the point of view of an input frequency disturbance now becomes:

$$\frac{Y}{X} = \frac{6.3s}{s^2 + 614\frac{\tau_2}{\tau_1}s + \frac{614}{\tau_1}}$$

With τ_1=500 µs and τ_2=3τ_1, the overall dynamics of the system are quite good. The step response is shown in Fig 7. As can be seen, the phase error due to a step change in frequency is eliminated in about 5 ms. In the actual system, any frequency changes are gradual and the phase error remains close to zero.

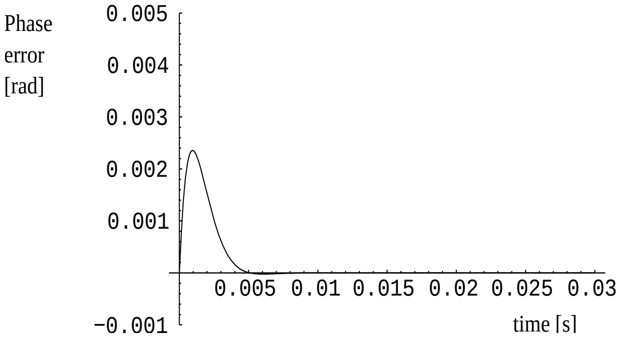

Fig 7: Step response with PI regulator

The PI regulator is implemented in a NIM standard module using classical analogue Op-Amp circuitry. Its simplified schematic diagram is shown in Fig 8. The first stage implements the actual PI regulator. The output stage using an LH0002 buffer is capable of driving a 50 Ω load.

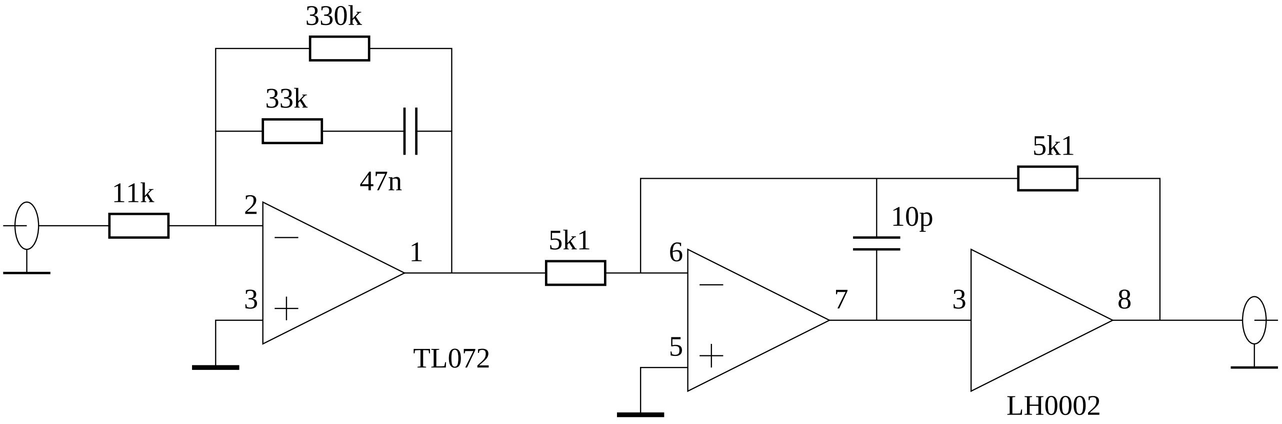

Fig 8: PI regulator schematics

Results

Measured results on PB^{54+} ion beams with and without the regulator are shown below. The phase error is considerably reduced by the regulator. The horizontal scale is 10 ms/div. The vertical scale corresponds to about 0.3 rad/div. Beam injection occurs 10 ms from the left edge of the screen. The disturbance 22 ms after injection corresponds to the beginning of the acceleration ramp.

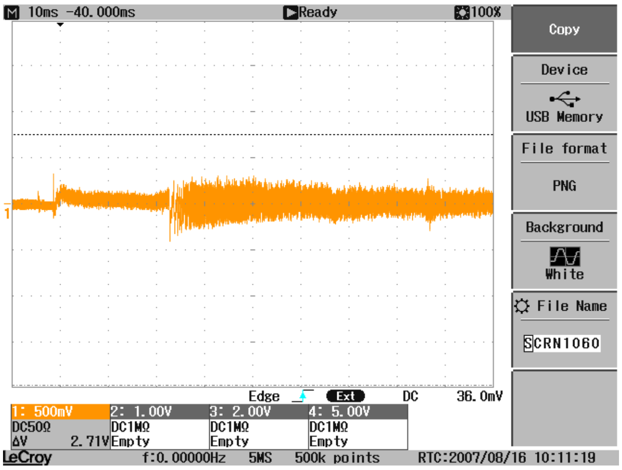

Fig 9: PI regulator ON

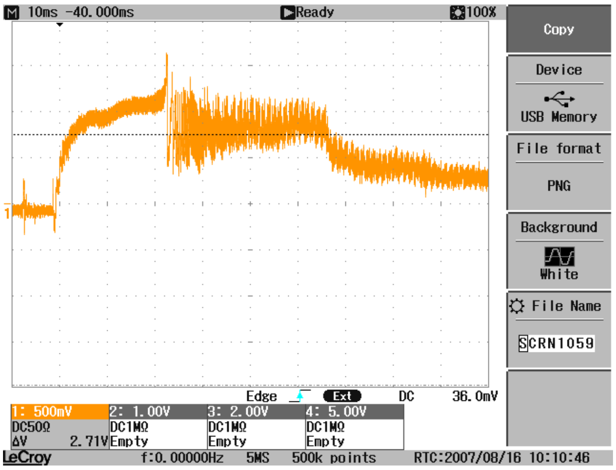

Fig 10: PI regulator OFF

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