A Digital Approach For Phase Measurement Applied To Delta-t Tuneup Procedure

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Abstract

Beam energy and phase in a Linac are important parameters to be measured in order to tune the machine. They can be calculated by the time of flight of a beam bunch over a known distance between two locations, and by comparing the phase of a cavity to the beam phase. The phase difference between two signals must be measured in both cases, in order to get the information required. The electronics to be used for this measurement must meet stringent requirements: high bandwidth, good accuracy and resolution have always been a challenge for classical analog solutions. A digital approach has been investigated, which provides a good resolution, accuracy independent on the phase difference value, good repeatability and reliability. Numerical analysis have been performed, showing the system's optimal performance and limitations. A prototype has been tested in the laboratory, which confirm the predicted performance, and proves the system's feasibility.

I. INTRODUCTION

The phase difference between the beam and the RF reference must be measured in order to get information for delta-t and phase scanning. Purpose of the delta-t measurement is to calculate the time of flight between two locations, to be compared with the model. This is done by switching a cavity OFF and ON and by calculating the difference between the two measurements. When two of these measurements are taken at two different locations, the difference between the two measured values gives information about the time of flight. The time can be then calculated using the following equation:

$$t = \frac{\Delta\phi}{\omega} \tag{1}$$

where $\Delta\phi = \Delta\phi_1 - \Delta\phi_2$, $\Delta\phi_1 = \phi_{1\,OFF} - \phi_{1\,ON}$, and $\Delta\phi_2 = \phi_{2\,OFF} - \phi_{2\,ON}$, with ϕ_{OFF} and ϕ_{ON} the phase difference between beam and RF reference at the locations 1 and 2, respectively when the cavity is OFF and ON.

Purpose of the phase scanning measurement is to changed the phase of the cavity respect to the RF reference, and to measure the phase variation of the beam with respect to the same reference. Since only phase differences are needed, none of the measurements requires absolute phase knowledge. The phase measurements requirements are shown in table 1.

Analog solutions have been used so far for these applications [1,2]. The problems connected with an analog system are well known: phase shifter linearity and temperature stability, limiter phase linearity, phase detector dynamic range, video bandwidth etc... All these reasons induced the author to find an alternative solution which didn't present these problems.

Table 1
Phase measurement requirements.

Item	Value
Phase dynamic range	360 deg
Resolution (minimum phase difference)	0.5 deg rms
Repeatability (respect to RF reference)	0.5 deg rms
RF frequency	428 MHz
Beam current dynamic range	5 - 50 mA
Sample time	5 μs - 35 μs
Repetition rate	10 Hz

The architecture shown in figure 1 solves the problems given by limiters and phase shifter, and realizes a 360 degrees phase detector with 200 KHz video bandwidth. The video bandwidth is limited by the technology used for this particular system, given the requirements. The current technology would allow to reach more than 2 MHz video bandwidth.

II. GENERAL ARCHITECTURE

The two input signals are undersampled and the phase difference is calculated using a curve fitting algorithm.

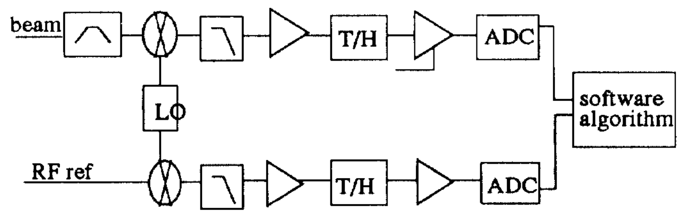

Figure 1. General architecture.

The main harmonic is selected and the signal is downconverted to a frequency compatible with the track and hold input analog bandwidth. The ADC's sampling rate is chosen in order to get a reasonable number of points in the measurement time interval.The software curve fits the two sampled signals with the best sinewave [3], and calculates the phase of the two signals. The phase difference is then computed.

The 428 MHz signals are downconverted to 60 MHz, the track and hold used is the Analog Devices AD9100, and the ADC is the Datel ADS118, a 12 bits ADC whose maximum sampling rate is 5 MHz. Two RF amplifiers are installed in front of the track and holds in order to provide the required

*Operated by the University Research Association, Inc., for the U.S. Department of Energy under contract No. DE-AC35-89ER40486 amplitudes in input. A variable gain amplifier after the track and hold in the beam signal channel compensates for the beam current fluctuations. The timing diagram of the sampling process is shown in figure 2.

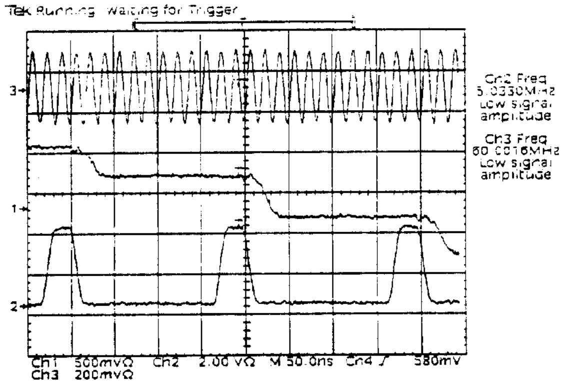

Figure 2. Timing diagram of the sampling process. Channel 3: input signal, channel 1: output data from the track and hold, channel 2: ADC sampling clock.

III. SOFTWARE ALGORITHM

A curve fitting algorithm fits the four parameters V_o, V_a, f_{in} and ϕ of a sinewave of form given in (2), by minimizing the error between the data points and the fit with successive approximations.

$$V_{in}(n) = V_o + V_a \cos(2\pi f_{in} n T_{sample} + \phi) \tag{2}$$

This expression can be rewritten as:

$$V_{in}(n) = V_o + V_a \cos(\omega_{in} T_n + \phi) \tag{3}$$

and using elementary trigonometric relations:

$$x_n = A\cos(\omega_{in} T_n) + B\sin(\omega_{in} T_n) + C \tag{4}$$

with $A = V_a\cos(\phi)$, $B = -V_a\sin(\phi)$ and $C = V_o$.

If the input frequency is known, eq. (4) can be rewritten as:

$$x_n = A\alpha_n + B\beta_n + C \tag{5}$$

with $\alpha_n = \cos(\omega_{in} T_n)$ and $\beta_n = \sin(\omega_{in} T_n)$, where the parameters to fit now are A, B, C. The advantage of this form respect to (2) is that there is a close form solution given by the algorithm described below.

Given a data record y_n of M samples, the total residual error ε of the measured data relative to the fit sine wave is:

$$\varepsilon = \sum_{k=1}^{M} (y_k - x_k)^2 = \sum_{k=1}^{M} (y_k - A\alpha_k - B\beta_k - C)^2 \tag{6}$$

Setting the partial derivatives with respect to the parameters being fit to zero gives:

$$\left\{\begin{aligned} 0 &= \frac{\partial\varepsilon}{\partial A} = -2\sum_{k=1}^{M}(y_k - A\alpha_k - B\beta_k - C)\,\alpha_k \\ 0 &= \frac{\partial\varepsilon}{\partial B} = -2\sum_{k=1}^{M}(y_k - A\alpha_k - B\beta_k - C)\,\alpha\beta_k \\ 0 &= \frac{\partial\varepsilon}{\partial C} = -2\sum_{k=1}^{M}(y_k - A\alpha_k - B\beta_k - C) \end{aligned}\right. \tag{7}$$

with some algebra:

$$\left\{\begin{aligned} \sum_{k=1}^{M} y_k\alpha_k &= A\sum_{k=1}^{M}\alpha_k^2 + B\sum_{k=1}^{M}\alpha_k\beta_k + C\sum_{k=1}^{M}\alpha_k \\ \sum_{k=1}^{M} y_k\beta_k &= A\sum_{k=1}^{M}\alpha_k\beta_k + B\sum_{k=1}^{M}\beta_k^2 + C\sum_{k=1}^{M}\beta_k \\ \sum_{k=1}^{M} y_k &= A\sum_{k=1}^{M}\alpha_k + B\sum_{k=1}^{M}\beta_k + CM \end{aligned}\right. \tag{8}$$

The fit parameters are given by the solution to the linear equation $Y = UX$, which is $X = U^{-1}Y$, where:

$$X = \begin{bmatrix} A \\ B \\ C \end{bmatrix};Y = \begin{bmatrix} \sum_{k=1}^{M} y_k\alpha_k \\ \sum_{k=1}^{M} y_k\beta_k \\ \sum_{k=1}^{M} y_k \end{bmatrix};U = \begin{bmatrix} \sum_{k=1}^{M}\alpha_k^2 & \sum_{k=1}^{M}\alpha_k\beta_k & \sum_{k=1}^{M}\alpha_k \\ \sum_{k=1}^{M}\alpha_k\beta_k & \sum_{k=1}^{M}\beta_k^2 & \sum_{k=1}^{M}\beta_k \\ \sum_{k=1}^{M}\alpha_k & \sum_{k=1}^{M}\beta_k & M \end{bmatrix} \tag{9}$$

The phase is then calculated by:

$$\phi = \operatorname{atan}\left(-\frac{B}{A}\right) + [1 - sign(B)]\frac{\pi}{2} \tag{10}$$

IV. PERFORMANCE

The results of the measurements in the laboratory are shown in figures 3-6, the measurement parameters in table 2. The phase was changed with a programmable delay line, and the value calculated by the system was compared with the phase measured with the Vector Voltmeter HP 8508. The Vector Voltmeter accuracy at the measurement's conditions is better than 0.4 deg. The absolute phase error versus the phase measured with the Vector Voltmeter is shown in figure 3.

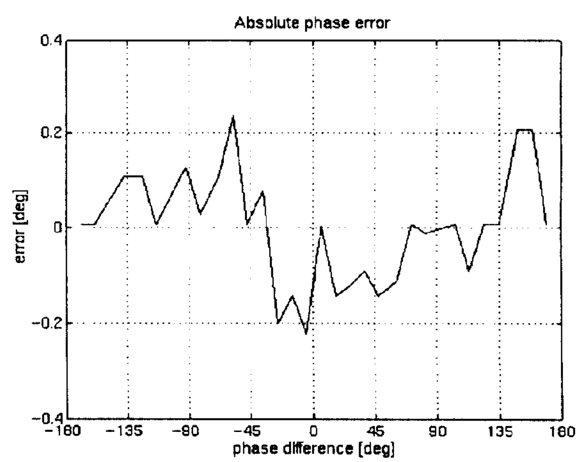

Figure 3. Absolute error versus phase difference.

The resolution of the system is shown in figure 4. Fifty measurements were taken at different phase angles, and the standard deviation calculated. This values limit both the system resolution and repeatability.

Table 2
Laboratory measurement parameters.

Item	Value
Input signal frequency	60 MHz
ADC sampling rate	5.04 MHz
Input signal	-17 dBm
ADC dynamic range	11 bits
Number of samples	25
Number of loops	50

The measurement parameters are specified by the requirements at table 1. The number of bits and number of samples are the optimized values experimentally determined, compared with the numerical simulation.

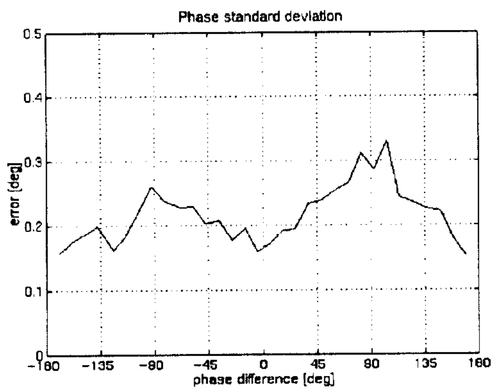

Figure 4. Standard deviation versus phase difference

The effect of the number of bits on the resolution is shown in figure 5, where experimental data are compared with the results of the simulation. The data points don't follow the theoretical plot, because of the noise on the ADC module used for the test. The digitized output shows 5 counts rms, when the analog input is terminated to ground.

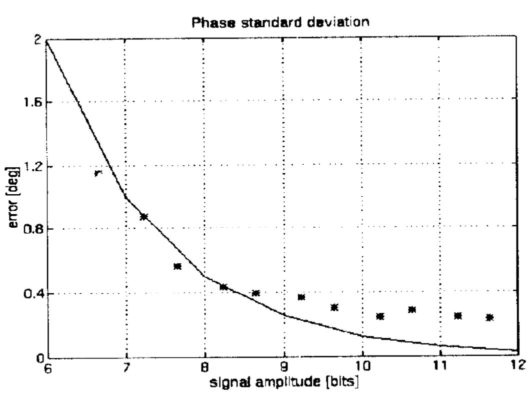

Figure 5. Standard deviation versus number of bits. Experimental data are compared to the simulation.

The algorithm chosen to calculate the phase proved to be very robust. The frequency value used for the curve fitting doesn't need to be determined better than 1%, and the sampling clock jitter is also not so critical, as shown in figure 6.

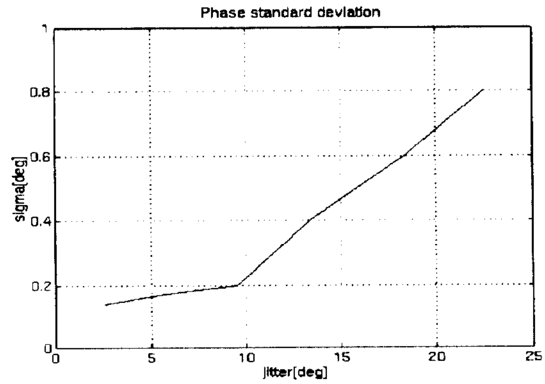

Figure 6. Phase standard deviation versus sampling clock jitter, expressed in degrees of the input frequency (60MHz).

The summarized system performance, shown in table 3, fully meet the system requirements. A better choice of the ADC module is expected to improve the system repeatability.

Table 3
Phase measurement performance.

Item	Value
Phase difference dynamic range	360 deg
Phase difference absolute accuracy	< 0.25 deg
Phase difference standard deviation	< 0.3 deg rms
Input signal dynamic range	-17 -52 dBm
Sample time	> 5 µs

V. ACKNOWLEDGEMENTS

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VI. CONCLUSION

A digital approach for phase measurement has been investigated, which provides good resolution, accuracy independent of the phase difference value, good repeatability and reliability. The system doesn't present problems typical of analog solutions. Numerical analysis have been performed, showing the system's optimal performance and limitations. A prototype has been tested in the laboratory, which confirms the predicted performance, and proves the system's feasibility. This system will be installed in the SSC Linac starting October 1993.

VII. REFERENCES

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[3] IEEE Std. 1057, "Digitizing Waveform Recorders" (1989)