DESIGN AND CALIBRATION OF A PHASE AND AMPLITUDE DETECTOR *

Zheqiao Geng#, Pengda Gu, Mi Hou, Guoxi Pei
Institute of High Energy Physics, the Chinese Academy of Sciences, Beijing 100049, China

Abstract

The phase and amplitude detector (PAD) is one of the key units of the phasing system for BEPCII linac. A new PAD based on I/Q demodulator has been constructed to measure the phase and amplitude of each klystron. To compensate the mismatches of the I/Q demodulator, a calibration algorithm using the adaptive LMS method has been developed to calibrate the I/Q demodulator, and most of the mismatches have been compensated after calibration. Some EMC methods have been adopted to minimize the influence of the noises in the klystron gallery, and the PAD has been running stably and successfully.

INTRODUCTION

The maximum phase fluctuation of each klystron allowed by BEPCII linac is±2°, so that the beam energy spread can be controlled to be less than 0.4% in the worst case[1][2]. It is very important to construct a stable and accurate PAD for phase and amplitude measurement.

I/Q demodulator can down convert a modulated signal to base band directly. It is easy to be used to measure the phase and amplitude simultaneously, and its circuit is very simple to be realized, so it is widely used to construct PAD. But I/Q demodulator suffers from mismatches such as DC offset, 90° phase imbalance and amplitude imbalance[3], which may draw remarkable errors to phase and amplitude measurement. A general calibration algorithm based on the adaptive LMS (Least Mean Square) method is used to calibrate the I/Q mismatches to a rather low level[4].

The greatest challenge for the PAD is to work in a very noisy environment in the klystron gallery. To minimize the influence of noises, some EMC methods, such as shielding, filtering must be correctly adopted.

PAD DESIGN

Hardware Design of the PAD

The block diagram of the PAD is shown in Figure1.

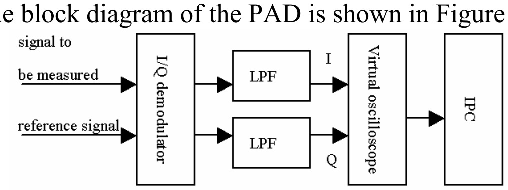

Figure1: The structure of the PAD.

The I/Q demodulator is constructed by a microstrip circuit board and two mixers working at the frequency of 2856MHz, which is shown in Figure 2. The LO input is split and phase shifted by a 90°-hybrid to form the reference signals, while the RF input is in-phase power divided as the signal to be measured, and the phase and amplitude of the RF signal is given by

$$\phi_0 = \tan^{-1}\left(\frac{Q}{I}\right) , \quad R = \sqrt{I^2 + Q^2} = kA_{RF} \cdot \qquad (1)$$

where I and Q is the output of the demodulator, A_{RF} is the amplitude of RF signal, k is a constant.

If the RF signal changes its phase from 0° to 360°, the trace of I/Q will be ideally a normal circle. But if there is any mismatch, the trace will be distorted to be an ellipse. Calibration algorithm is needed to compensate the mismatches.

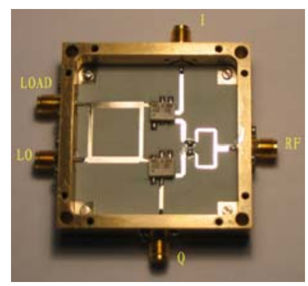

Figure 2: The I/Q demodulator.

The virtual oscilloscope is used as a fast digitizer for sampling the I/Q signals. Its sampling rate is 50MS/s with a 12bit vertical resolution. Sampled data is transferred to an industrial computer where phase and amplitude are calculated.

Calibration of the PAD

The error of the PAD is mainly from the mismatches of the I/Q demodulator, including DC offset, phase and amplitude imbalances. To compensate the mismatches, the frequency of RF signal is changed to be a little different from the frequency of LO signal. Then the I/Q outputs will be two sine waves of low frequency. Because of the mismatches, the two sine waves will have different amplitudes and phase error off 90°, and the trace of I/Q will be an ellipse, which is shown in Figure 3.

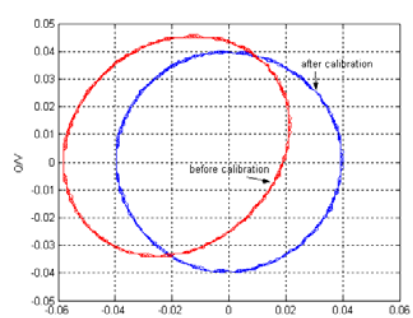

Figure 3: The I/Q trace before and after calibration.

*Work supported by BEPCII project
#gengzq@mail.ihep.ac.cn

0-7803-8859-3/05/$20.00 ©2005 IEEE

A calibration algorithm is to draw ideal I_0/Q_0 values from the distorted I/Q values measured in practice. The relationship of I_0/Q_0 and I/Q can be written as

$$I_0 = f\left(I,Q\right), \quad Q_0 = g\left(I,Q\right). \tag{2}$$

where f and g are functions to be decided by evaluating the I/Q mismatches. A convenient way to get f and g is to use the Taylor expansion

$$\begin{aligned} I_0 &= a_0 + \sum_{n=1}^{n=N}\left(a_n I + b_n Q\right)^n + R_I(N), \\ Q_0 &= c_0 + \sum_{n=1}^{n=N}\left(c_n I + d_n Q\right)^n + R_Q(N). \end{aligned} \tag{3}$$

Remove the residual items and combine the unknown coefficients, equation (3) can be rewritten as

$$\begin{aligned} I_0 &= a_0 + a_1 I + a_2 Q + a_3 I^2 + a_4 IQ + a_5 Q^2 + \cdots, \\ Q_0 &= b_0 + b_1 I + b_2 Q + b_3 I^2 + b_4 IQ + b_5 Q^2 + \cdots. \end{aligned} \tag{4}$$

where a_n, b_n (n=0,1,2…) are coefficients to be decided.

To get the unknown coefficients in equation (4), we sample the I/Q sine waves mentioned above. The I waveform can be fitted to be a Fourier series (the residual item has been removed)

$$I(t) = I_{DC} + \sum_{i=1}^{i=M}\left(m_i \cos(i\omega t) + n_i \sin(i\omega t)\right). \tag{5}$$

Assume the desired values of the I/Q waves measured by the PAD to be

$$\begin{aligned} I_d(t) &= \sum_{i=1}^{i=M}\left(m_i \cos(i\omega t) + n_i \sin(i\omega t)\right), \\ Q_d(t) &= \sum_{i=1}^{i=M}\left(m_i \cos(i\omega t - \pi/2) + n_i \sin(i\omega t - \pi/2)\right). \end{aligned} \tag{6}$$

note that the order N and M selected in equation (3) and (6) is decided by the requirement of accuracy.

Define the vectors

$$\begin{aligned} \tilde{a} &= \left[a_0, a_1, a_2, a_3, a_4, a_5 \cdots\right]^T, \\ \tilde{b} &= \left[b_0, b_1, b_2, b_3, b_4, b_5 \cdots\right]^T, \\ \tilde{u} &= \left[1, I, Q, I^2, IQ, Q^2 \cdots\right]^T. \end{aligned} \tag{7}$$

then the adaptive LMS method is used to get the unknown coefficients in equation (7). For example, to get the coefficients $\tilde{a}$, follow the steps

i) $\tilde{a} = 0$.

ii) $k = 1, 2 \cdots$

$$\begin{aligned} e_I(k) &= I_d\left(k\right) - \tilde{a}^T\left(k-1\right)\tilde{u}\left(k\right) \\ \tilde{a}\left(k\right) &= \tilde{a}\left(k-1\right) + \mu_I \tilde{u}\left(k\right) e_I\left(k\right). \end{aligned} \tag{8}$$

where e_I is the error item and μ_I is the convergence factor.

The I/Q trace after calibration is shown in Figure 3. It is shown that most of the mismatches are compensated by the calibration algorithm.

PAD TEST

In order to measure the phase error of the PAD, a precise phase shifter, which has been calibrated by the network analyzer, is inserted into the RF channel of the PAD. Tune the phase shifter and measure the phase change with the PAD, then compare it with the results calibrated by the network analyzer, and the phase error of the PAD is shown in Figure 4. Because the PAD is used to measure a small phase difference, the phase error won't cause much trouble on the operation of the phasing system.

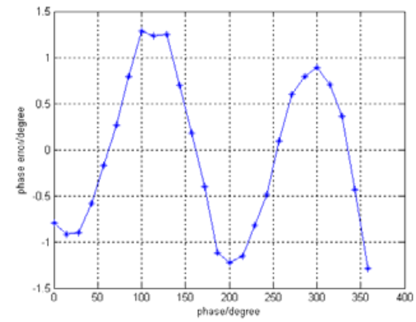

Figure 4: Phase error of the PAD

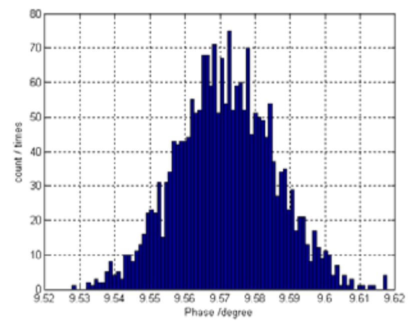

Figure 5: Distribution of the phase.

Measure the same phase difference for many times, and Figure 5 shows the phase distribution. It is shown that the phase resolution of the PAD is about 0.05°, which is suitable to measure a small phase change.

The PAD is not very sensitive to the environment temperature. The phase drift due to the temperature change is less than 0.05°/°C, so it is stable enough for the phasing system of BEPCII linac. The dynamic range of the RF input power for both phase and amplitude measurements is from –15dBm to 0dBm, in which the PAD will give best results.

EMC CONSIDERATIONS

The PAD will be working in the klystron gallery of BEPCII linac, so some EMC methods must be adopted to minimize the influence of the klystron noises. The following steps are taken in the PAD chassis

- Power filter is used to remove the noises in the supply power.
- A new shielding box is used to avoid the radiation noises into the virtual oscilloscope.
- Two band pass filters are added into the two 2856MHz channels.
- Ferrite rings are added into the I/Q IF output channels.

- Adaptive digital filters are adopted in the phasing program to remove the residual random noises.

By these techniques, most of the noises are removed. Figure 6 shows the phase change of klystron #1 measured by the PAD.

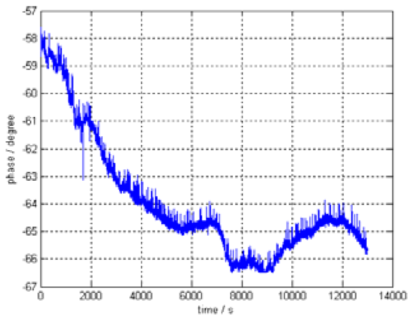

Figure 6: Phase change measured by the PAD.

CONCLUSIONS

A new PAD based on I/Q demodulator is constructed and tested both in laboratory and in the klystron gallery. To compensate the mismatches of the I/Q demodulator, a calibration algorithm using LMS method is developed, by which, the mismatch of the I/Q demodulator can be reduced to a rather low level. Experiments show that the PAD has a high resolution and large dynamic range, and it is stable enough to be used in the phasing system of BEPCII linac. Future plan is to improve the phase accuracy of the PAD by using better devices and by improving the calibration algorithm.

REFERENCES

[1] Guoxi Pei, “Overview of BEPCII Linac Design”, LINAC’02, Gyeongju, Korea, August 2002.

[2] Pengda Gu and Zheqiao Geng, “RF phasing system for BEPCII Linac”, APAC’04, Gyeongju, Korea, 2004.

[3] S. Sabah and R. Lorenz, “Design and calibration of IQ-Mixers”, EPAC’98, Stockholm, Sweden, 1998, p.1589.

[4] J.K. Cavers and M.W. Liao, “Adaptive compensation for imbalance and offset in direct conversion transceivers”, IEEE Transactions on Vehicular Technology, Vol. 42, No.4, November 1993, p. 581.

0-7803-8859-3/05/$20.00 ©2005 IEEE