

Construction of the Phasing System for BEPC II Linac

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Abstract In order to get high beam quality, a RF distribution system is required, with minimal phase drifts and errors in the BEPC II linac. The additional installation of phase reference cables and monitoring equipments and stable RF distribution for BEPC linac are finished. The master oscillator is chosen to offer RF signal with low phase noise and a stable phase distribution system is built to deliver RF signal to each klystron. A phase and amplitude detector is constructed to measure the phase precisely and an IΦA unit is used for a phase shifter. Control software based on EPICS is used to connect all the units of the system, and a phasing method based on BPM is adopted to optimize the phase of each klystron. Now the phasing system is installed and tested in the klystron gallery of the BEPC II linac.

Key words linac, PAD, I/Q demodulator

1 Introduction

In a linear accelerator, as the phase drift, the central energy of the beam will change and the energy spread will get worse, the beam orbit and current will change, and much instability will rise. The RF phase drift will cause many problems on beam quality. The BEPC II linac requires much higher beam quality than BEPC^[1], especially for the positron beam, which is shown in Table 1. To meet these requirements, it is necessary to build a phase control system for 200m long linac. The RF phase control system is established to compensate the phase drift due to various change factors. The phasing procedure can get the optimized phase for improving the beam quality, and the phase feedback control will maintain the

Table 1. Positron beam quality of BEPC and BEPC II.

	BEPC	BEPC II
energy of e^+	1.3GeV	1.89GeV
current of e^+	4—5mA	40mA
$(\Delta E/E)^+$	$\geq 0.8\%$	$\leq \pm 0.5\%$
filling rate of e^+	1—5mA/min	$\geq 50\text{mA}/\text{min}$

running status for long-term stability.

2 Phase distribution system design and construction

The BEPC linac consists of approximately 563.05m-long disk-loaded accelerating sections, powered by approximately 16 high-power klystrons. This signal is distributed along the 200m length on a special Phase Reference Line (PRL), and is supplied to the first klystron through 1kW pulse solid amplifier for generation of the pulsed drive for the accelerator klystrons. The pulsed drive signal is distributed along the 200m length by a small (1.75 inch) rigid coaxial waveguide and the coaxial waveguide was used to deliver the high-power pulsed drive signal from the first klystron to the other 15 main klystrons by the main drive line in the linac. Each klystron is instrumented with a phase detector (PAD) which measures the difference between the phase of the reference line and the RF entering the accelerator^[2], as shown in Fig. 1.

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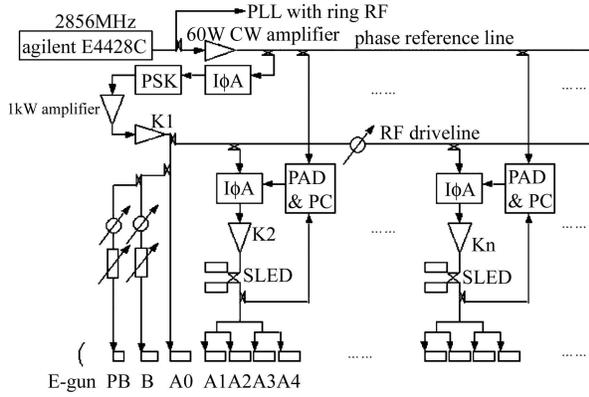


Fig. 1. BEPC linac RF distribution.

2.1 Master oscillator and PRL

Agilent E4438C ESG and AR CW solid amplifiers were chosen as the system master and were put in the thermostatic chamber. The Phase Reference Line (PRL) is Andrews Heliax coaxial cable, hung from the ceiling, and each length is insulated. Narda RF couplers are installed between lengths. The cable has a temperature coefficient of 5ppm/°C. That means for the 200m-long klystron gallery with a temperature fluctuation of $\pm 1.0^\circ\text{C}$, the reference phase will drift more than ± 4.0 RF degree. So we must put the cable in a water pipe to limit its temperature to within $\pm 0.2^\circ\text{C}$. The operating temperature is 21°C for the PRL cooling system.

2.2 IΦA unit and PAD

IΦA unit is composed of an isolator and one motorized (stepper) phase shifter and one continuously variable attenuator. It's a controlled unit. The phase and amplitude detector (PAD) consists of an analog I/Q demodulator and a two-channel virtual oscilloscope with 12-bit ADCs, which is shown in Fig. 2. The virtual oscilloscope is put in a shield box to avoid strong EMI. The I/Q demodulator down converts the RF signal directly to the base band. Virtual oscilloscope digitalizes the base band signals and then transfers them to the computer, where the phase and amplitude are calculated.

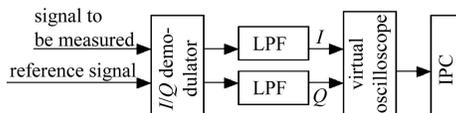


Fig. 2. The PAD unit.

The I/Q demodulator is the key part of the PAD, but it suffers from amplitude and phase imbalances, in which it may draw remarkable error to the measurements. To reduce the influence of the imbalances, an on-line calibration method is adopted. The calibration formula is shown below^[3]

$$\begin{bmatrix} I_0 \\ Q_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ a_1 & a_2 \end{bmatrix} \begin{bmatrix} I + a_3 \\ Q + a_4 \end{bmatrix}, \quad (1)$$

where I and Q are the base band signals measured respectively in practice. I_0 and Q_0 are the signals after calibration. And a_1 , a_2 , a_3 and a_4 are calibration coefficients to be decided.

At each klystron station, there is a motorized phase shifter, which has been carefully calibrated by the network analyzer. The phase shifter is moved by a certain angle θ_i , and the phase shift measured with the PAD. Assume the measured I/Q data before and after one movement are (I_{si}, Q_{si}) and (I_{ei}, Q_{ei}) , then the non-linear fitting can be carried out:

$$\text{err}_i = \theta_i - \left\{ a \tan \left[\frac{a_1(I_{ei} + a_3) + a_2(Q_{ei} + a_4)}{I_{ei} + a_3} \right] - a \tan \left[\frac{a_1(I_{si} + a_3) + a_2(Q_{si} + a_4)}{I_{si} + a_3} \right] \right\}, \quad (2)$$

$$f(a_1, a_2, a_3, a_4) = \sum_i \text{err}_i^2,$$

The calibration result is shown in Fig. 3. The upper part of the figure shows the I/Q trace before and after calibration, and the lower part of the figure shows the residual phase error after calibration, which is less than 1.5 RF degree.

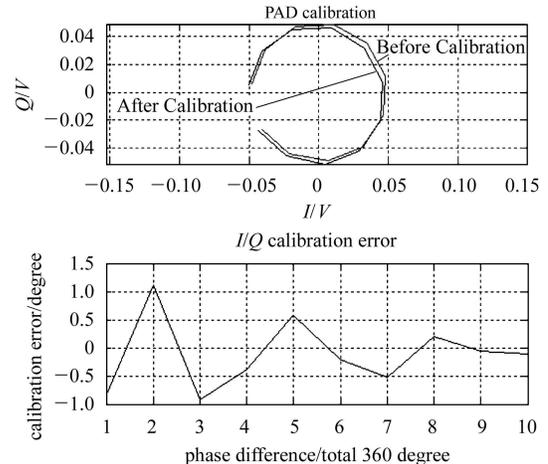


Fig. 3. PAD calibration.

2.3 EPICS based control software

The control software structure of the phasing system is shown in Fig. 4. There is an IPC near each klystron station and the phase and amplitude of each MK could be measured at real time. The phasing system server is placed in the linac central control room as shown in Fig. 5.

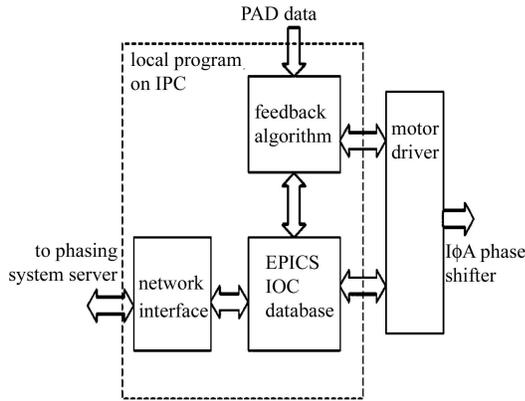


Fig. 4. Control flow from/to IPC.

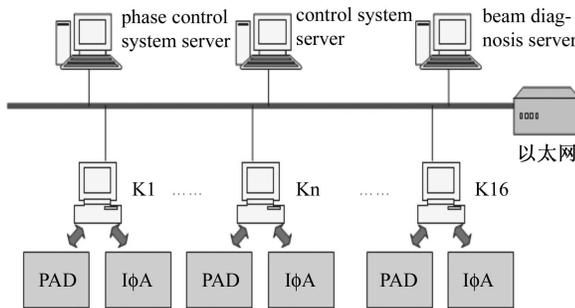


Fig. 5. Phasing control unit distribution.

3 The phasing method (energy maximizing method for phasing)

Even with the phasing system and such automatic stabilization tools, however, phasing of the accelerator is still periodically required to correct many changed factors which could not be compensated for; for example, those caused by these components which are beyond the phasing block loop on the BEPC RF distribution systems. So, an automated procedure has been developed to allow the phasing of the linac using the beam as the primary phase reference. Analysis is done using model driven analysis of the Beam

Position Monitor data for determination of the observable beam parameters: coordinates X, X', Y, Y' are position and angle, and dE is energy error. By moving the phase shifter of the $I\Phi A$ within a certain range of the phase (or angle of the rotary vane), measuring the beam energy using the BPM and using the least square fitting of the measured data, the maximum position from the fitting function is found. All of these sequence procedures are to adjust the phase for each section to maximize the beam energy.

4 System test

The hardware of the phase control system has been installed in the klystron gallery. And the control software has been developed and tested. The total system has been running for almost three months and proved to be reliable.

4.1 Phasing of the linac

By energy maximizing method, the phase of each klystron is optimized. Both the data acquisition and curve fitting are done automatically by an EPICS based program. Fig. 6 shows the phasing result of one of the klystrons.

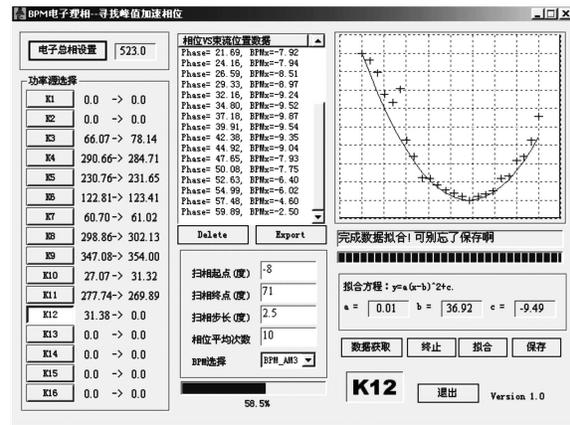


Fig. 6. Phasing result of klystron No. 12.

4.2 Phase feedback test

To compensate the phase drift of the klystron, a feedback loop is added to each klystron station. The PAD measures the phase of the klystron output, and then compares it with the reference phase, which can be drawn from the phasing procedure. If the phase error exceeds the range allowed, the phase shifter in

$I\Phi A$ will be adjusted to remove the error. In Fig. 7(a), the phase of klystron No.12 was measured for one day

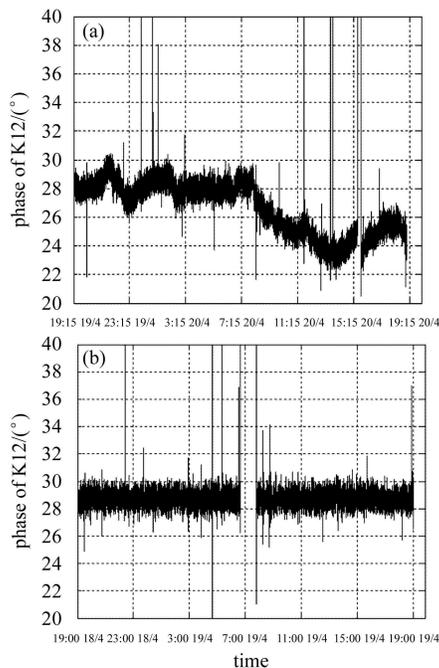


Fig. 7. (a) Phase of klystron No.12 with no feedback; (b) Phase of klystron No.12 with feedback on.

with no feedback, while Fig. 7(b) shows the phase of the same klystron for one day with feedback on. The effect is obvious.

5 Conclusion

Each klystron is equipped with an independent phase read back and control instrumentation (PAD), which provides the operation staff of the accelerator with nearly 16 phase parameters to adjust for optimal machine operation. The RF controls and the linac control system are designed to maintain the RF phase output of each klystron at the values in the on-line database, as compared to a local RF reference. The control system maintains the phase of the machine, directly compensating for changes induced by weather, temperature, modulator voltage, and other factors out of our control. In any way the function of the phasing system is to optimize and adjust the phase of the 16 klystrons so that the energy of accelerated electron or positron beam is maximized and energy spectrum width is held to a minimum^[4].

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BEPC II 直线加速器相控系统的建立

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摘要 为了获得高品质束流, BEPC II 直线加速器采用相位系统来优化和控制 16 个速调管的 RF 相位. 相控系统分布: 低相位噪声射频信号源作为直线系统的主振荡器; 加以恒温水系统控制的稳定相位参考线用以提供相控 PAD 装置 Local 输入; 基于 EPICS 操作界面的控制软件用以连接 16 个控制环路的精确测量并对加在每个速调管前级输入的 $I\Phi A$ 移相器加以调控; 基于能量最大法相位分析测试方法的引入对系统的测试进行了优化从而提高了系统的测试精度. 整个系统的建立最终控制了直线因温度缓慢变化引起束流相对加速微波相位偏移而造成的能散度变化.

关键词 直线加速器 相位幅度测试 I/Q 解调器

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