LLRF CONTROL SYSTEM FOR PKU DC-SC PHOTOCATHODE INJECTOR

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Abstract

A digital low level RF control system based on Field-Programmable Gate Array (FPGA) with high precision is being developed for the stable operation of upgraded Direct Current-Superconductive (DC-SC) photocathode injector at Peking University. The design of this Low level radio frequency (LLRF) control system is described, including both hardware and internal algorithm. The system is designed to achieve the requirement of $\pm 0.1\%$ for amplitude stability and $\pm 0.1^o$ for phase stability.

INTRODUCTION

The DC-SC photocathode injector developed by Peking University is one candidate of low emittance, high brightness electron beam sources. The concept is to integrate a Pierce DC gun and a superconducting cavity to solve the compatibility of the photocathode and the superconducting cavity [1]. A prototype photocathode injector with a Pierce gun and 1.5 cell superconducting cavity was manufactured in 2002, and the feasibility of the DC-SC photocathode injector was demonstrated by the beam experiments in 2004 [2]. Recently the DC-SC photocathode injector has been upgraded with a 3.5 cell superconducting cavity made of large grain size niobium sheets and working at 2K (Fig. 1). This cavity has been tested in JLab and the accelerating gradient E_{acc} and Q_0 value reached 23.5 MV/m and 1.2×10^{10} respectively. [3]

The Q_{ext} of main coupler is set at 1.2×10^{10} and the bunch repetition of electron beam for upgraded injector is 81.25 MHz. Such design is to meet the requirements for research and development of Peking University Energy Recovery Linac (PKU-ERL) and Free Electron Laser (PKU-FEL). In order to maintain the stability of the electromagnetic field in the 3.5 cell cavity, in this paper, the design of LLRF system for the upgraded DC-SC injector is described, including both hardware and internal algorithm.

DETUNING INSTABILITIES OF 3.5 CELL CAVITY

Microphonics, beam loading effect and Lorentz force are the main detuning instabilities for SRF accelerators. Therefore the LLRF control system is very important for the stable operation of accelerator system based on SRF technology.

Microphonics results from mechanical vibrations of surrounding environment and it is stochastic. Beam loading effects which widely exist in high energy accelerators are

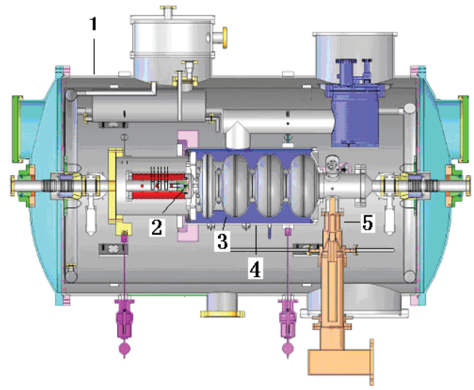

Figure 1: [1] Thermostat, [2] Photocathode (Te2Cs), [3] 3.5 cell LG Nb cavity, [4] Liquid Helium tank, [5] Main coupler

caused by the field excited by the beam. And Lorentz force detuning results from certain radiation pressure generated by RF electromagnetic field, which takes effects on SRF cavity surface and makes it deform.

Considering the 3.5 cell cavity will be operated on 10 MV/m, such gradient does not reach the threshold value of Lorentz force (usually 15–20 MV/m) and the designed average beam current at the first step is about 1 mA, the influence of Lorentz force and beam loading effect are not very important.

For the 3.5 cell superconducting cavity in the DC-SC photocathode injector which has thin shell construction, microphonics is the main detuning instability. The main sources are the vibration from the assistant equipment such as liquid helium and water cooling systems. Though stiffing ring is used to prevent the cavity from being deformation the LLRF control system is needed for further tuning.

The relationship between the detuning angle ϕ and the frequency variation can be presented as Formula (1),

$$tan\phi = 2Q_L \frac{\Delta\omega_0}{\omega_0}, \quad (1)$$

here Q_L is the load quality factor. For the DC-SC injector system, $Q_L = 1.2 \times 10^7$. If the frequency variation caused by microphonics is 5 Hz, the detuning angle would be 5.27^o. It is serious for the stable operation of our injector with a 3.5 cell cavity.

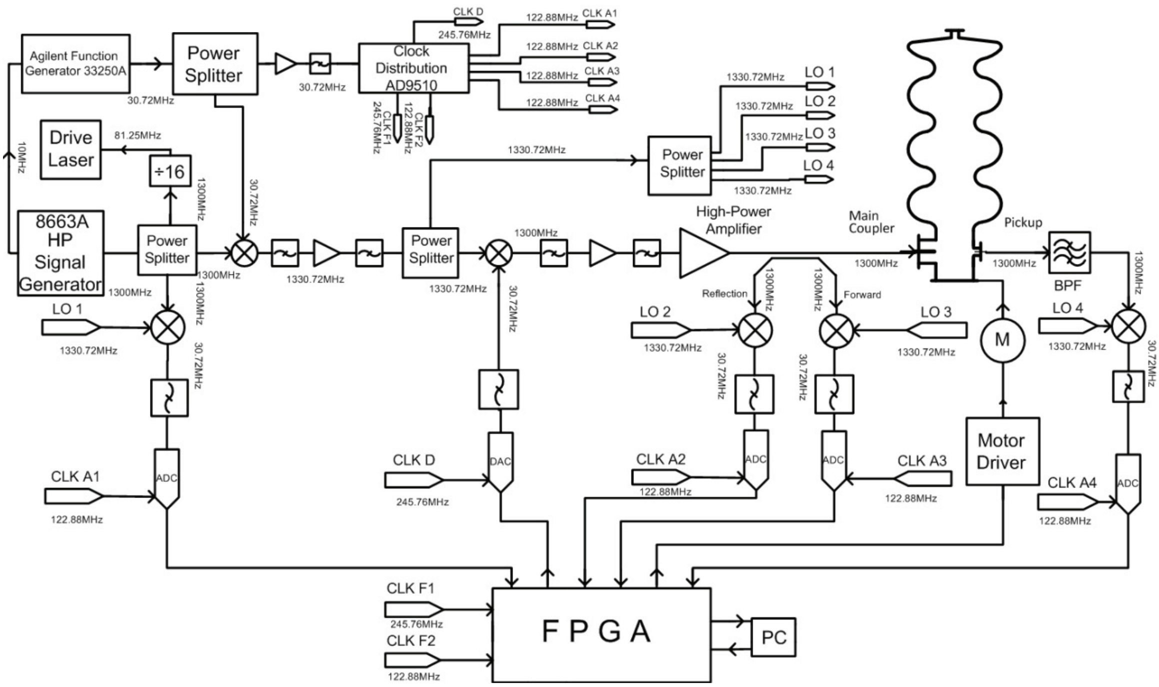

Figure 2: The schematic of the control system for PKU SRF photocathode injector.

THE DESIGN OF LLRF CONTROL SYSTEM

Compared with some analog systems with the precision of $\pm 0.1\%$ for amplitude and of $\pm 0.1\%$ for phase, the digital LLRF control system has the advantages of high precision and flexible algorithm. Therefore we choose digital technique to meet the high requirement of DC-SC injector at Peking University. The schematic of the digital LLRF control system is shown in Fig. 2, which includes the feedback control loops for amplitude control and phase control. By comparing the pick-up signal with the reference value, the program in FPGA can adjust the output signal to compensate the deviation, and thus make the system stable.

Hardware of the Control System

Local oscillator (LO) is one of the most important parts in the above system. HP Signal Generator 8663A is used to generate 1.3 GHz RF signal, which can be mixed with the 30.72 MHz signal generated by Agilent Function Generator 33250A to get the LO signal with 1330.72 MHz. The internal reference signal with frequency of 10 MHz can ensure both generators work on the same locked phase.

The other important part is the scheme of clock distribution. We use the reference signal with frequency of 30.72 MHz for the reference clock (CLK) of AD9510. The center frequency of voltage controlled oscillator (VCO) of AD 9510 is 245.76 MHz, and we can obtain eight route signals, four with a frequency of 122.88 MHz for ADC and FPGA, and the other four with 245.76 MHz for DAC.

The advanced Stratix IV GX FPGA Development Kit is chosen for developing because of its outstanding performance. Compared with the former products, the Stratix IV series adopt the production process of low power consumption, high performance, and high density, which efficiently improve the operation speed and the interior max clock frequency. The daughter board Analog-to-Digital and Digital-to-Analog (ADDA) data conversion Terasic P0035 with dual high-speed 150 MSPS A/D and 250 MSPS D/A channels is chosen for its high sampling rate.

Internal Algorithm of FPGA

Internal algorithm of FPGA as shown in Fig. 3 is used in our system. The amplitude and phase information are abstracted from IF signal through I (In-phase) and Q (Quadrature) sampling and CORDIC algorithm. Comparing them with the reference value, deviations of amplitude and phase are obtained and used to adjust the amplitude and phase of input signal. The PI controller is used to make the deviation signals proper for adjustment and DDS rebuilds the sine signal. Finally, through DAC, such a series of digital signals are converted to analog signals. Therefore, the amplitude and phase of RF signal can be kept within a small range.

IQ sampling has been widely used in the LLRF control system because of the advantage that signals are orthogonal and do not interfere each other. IF signal from down-conversion is sampled by ADC to get a series of signal: I, Q, $-I$, $-Q$, ... as shown in Fig. 4.

IQ signal can be converted to amplitude and phase form through CORDIC algorithm based on coordinate rotation in a plane. I and Q are regarded as the initial components $[X_0, Y_0]$ of a vector. Rotating this vector with an angle of

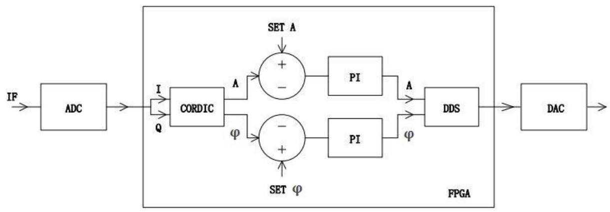

Figure 3: Internal Algorithm of FPGA.

$\alpha_i = \arctan(2^{-i})$ each time until y-component tends to 0, amplitude is the value of x-component of the final vector, while phase can be expressed as $\theta = \sum_0^{n-1} \sigma_i \alpha_i, \sigma_i \in -1, 1$, here σ_i presents the direction of rotation and is decided by quadrant where the vector is.

CONCLUSION

For stable operation of the DC-SC photocathode injector, a digital low level control system has been designed. Through careful design of control loops, careful choice of hardware and suppressing the disturbances causing the phase error, the control precision of our LLRF system should achieve the requirement of $\pm 0.1\%$ for amplitude and of $\pm 0.1^o$ for phase stability. Now the system is being tested and will be used for the operation of the DC-SC injector in the near future.

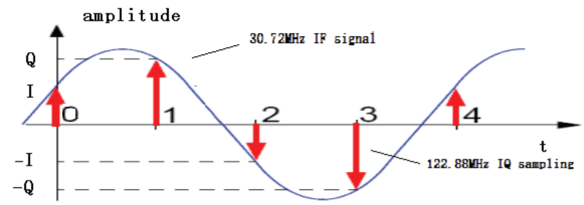

Figure 4: The IQ sampling sketch map.

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