MICROTCA.4-BASED LLRF SYSTEM FOR SPOKE CAVITIES OF C-ADS INJECTOR I

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Abstract

The C-ADS Injector I is being built in IHEP, which includes 14 beta=0.12 superconducting single spoke cavities enclosed with two cryomodules under 2 K. The MicroTCA.4-based Low Level RF (LLRF) system provides GDR mode for the operation of the cavities. The LLRF system supports both CW and duty-adjustable pulsed operation modes for the high power source and the cavities. The firmware of the FPGA controller and the EPICS IOC software has been upgraded during the last half year adding feedforward and abnormal detection. The operator interface (OPI) software and automatic operation script are also described. The MicroTCA.4 platform runs well for the beam commissioning of the Injector I. Some gained experiences with stable beam operation are also shown.

INTRODUCTION

The China-Accelerator Driven Sub-critical System (C-ADS) project is a strategic priority program to solve the nuclear waste problem in China[1]. To achieve high stability and availability, the 1.5GeV CW proton accelerator uses two injectors - Injector I and Injector II which are designed and built by Institute of High Energy Physics (IHEP) and Institute of Modern Physics (IMP) respectively. The layout of the Injector I is shown in Fig. 1. The Injector I consists of the ECR ion source, the LEBT, the CW room-temperature RFQ, the MEBT1 and 14 beta=0.12 superconducting Spoke cavities which are enclosed in two cryomodules under 2 Kelvin. The 10mA CW proton beam is accelerated to 10MeV at the exit of the injector I and the frequency of the RFQ and superconducting cavities is 325MHz.

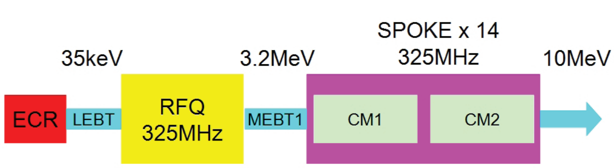

Figure 1: Layout the Injector I of C-ADS project.

REQUIREMENT ANALYSIS

The LLRF system is responsible for the control, operation and protection of RFQ, two bunchers in the MEBT1 section and the following 14 Spoke cavities. The basic requirements of LLRF system include:

1. The acceptable beam loss rate is less than 1W/m which is quite challenging especially in the high energy section; the accelerating field must be quite stable and the interlock from LLRF system must be quick and strong enough;

2. The phase and amplitude stability should be better than ±0.5° and ±0.5% according to beam dynamics;

3. The interlock signals should be provided for the fast machine protection system such like quench, loss of close-loop and reverse power overshoot etc;

4. The LLRF system supports CW and pulsed operation mode for the high power source and the cavities;

5. The LLRF system provides convient interface to the higher control system, like accelerating field ramping, automatic phase scanning, easily recovery from system collapse etc;

SYSTEM DESIGN AND RESULTS

Spoke Cavity

The Spoke cavity is one of the TEM-class cavities which is suitable for low beta (0.1<beta<0.8) condition. In C-ADS Injector I, seven 325MHz single spoke cavities are assembled in one cryomodule (CM) [2] and each cavity is driven by one set high power source. The spoke cavities in the CM1 are shown in Fig. 2.

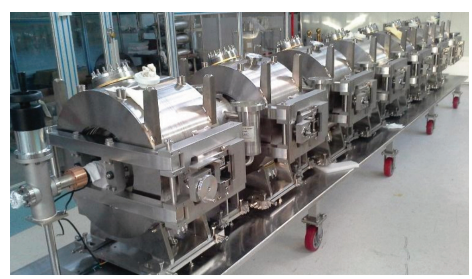

Figure 2: Spoke cavities in one cryomodule.

LLRF System Overview

Each cavity is controlled by a single controller. The principle of the LLRF system is illustrated in Fig.3. The upconvertor(UPC) upconverts the IF signal to RF and drives the high power source - the 10kW CW solid state amplifier for each Spoke cavity. The pickup, forward and reverse signals are downconverted (DWC) to IF signal. All the RF signals are synchronized with the reference.

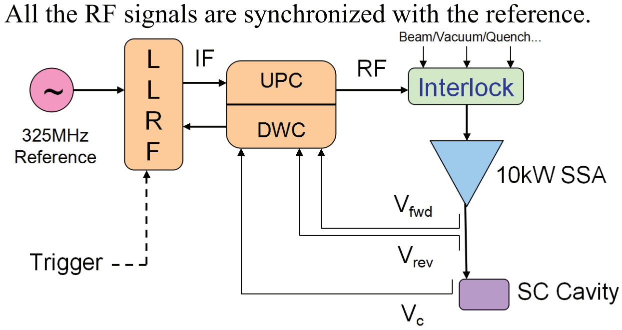

Figure 3: Principle of the LLRF system.

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In order to achieve the high availability of the accelerator, we choose the MicroTCA.4 standard SIS8300 board [3] as the LLRF controller. The digital signal flow in the FPGA is shown in Fig. 4. The MicroTCA.4 standard controller generates the IF signal and digitizes the IF signals through I/Q sampling. The phase and amplitude are calculated from I/Q components by the pipeline CORDIC algorism. The PI feedback is implemented in FPGA for both phase and amplitude paths. The feed-forward setpoints are also added for the heavy beam loading case when the accelerator runs in pulse mode and the proton beam is longer than 50us.

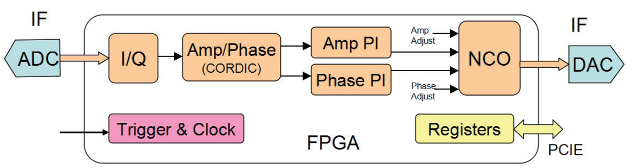

Figure 4: The digital flow in the FPGA.

Trigger System

The accelerator is supposed to run in CW mode, however it also needs to run in pulsed mode as in the conditioning and pre-commissioning period. So a complex trigger system is designed to satisfy the CW, self-trigged and external-trigged condition. The trigger system is illustrated in Fig. 5. Two switches which are controlled by a two-bits register select different trigger modes. The self-trigger is derived from the system clock and this mode is very useful and flexible for the pulsed conditioning of the couplers and cavities. The external trigger is derived from the timing system which is mostly used for the standard pulsed operation or with the feed-forward control for the beam loading compensation.

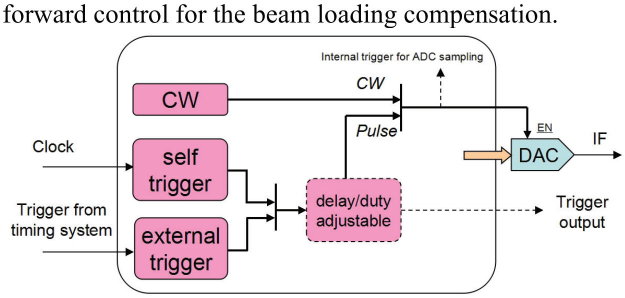

Figure 5: The trigger system.

Results

The typical open loop (GDR mode) spectrum of one cavity (Cavity01) is displayed in Fig. 6. The sidebands and noise are mostly from electro-mechanical coupling and microphonics.

With the phase and amplitude loop closed but without using piezo for the frequency control, the spectrum is displayed in Fig. 7, the SFDR is better than 85dB within the cavity bandwidth. The long term stability of the phase and scaled amplitude of the cavity is shown in Fig. 8, the peak-to-peak errors of the phase and amplitude are within 0.2° and 0.3% respectively. The accelerating gradient is about 5.0MeV/m.

The clock of the DACs on the SIS8300 controller board is given by the FPGA which brings very large jitter. Base band I/Q upconvertor and new version SIS8300L board with better clock performance is being evaluated, the phase and amplitude stability will be impoved further. In system level, lower lorentz coefficient and frequency controling with piezo would also reduce the sideband and improve system stability.

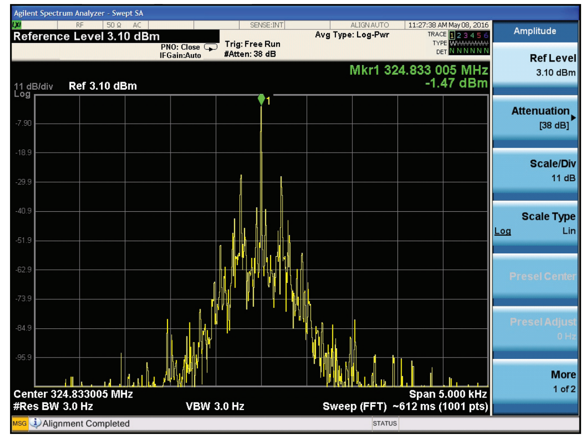

Figure 6: The open loop spectrum.

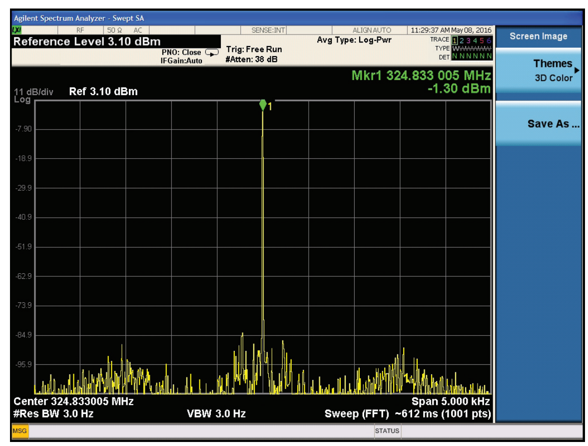

Figure 7: The close loop spectrum.

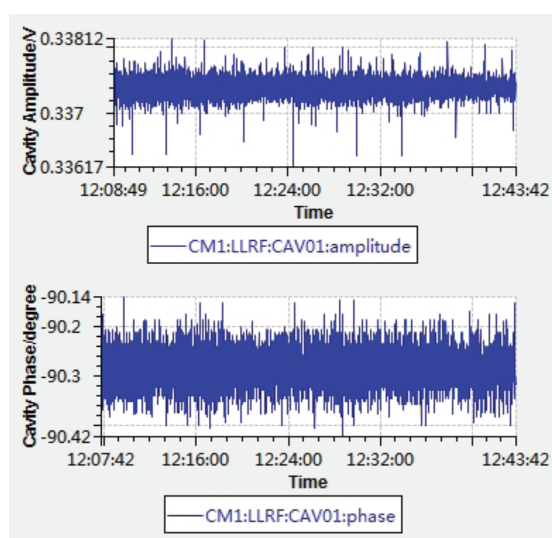

Figure 8: Long-term phase and amplitude stability.

Feed-Forward

Feed-forward control method is added when the cavity runs in CW mode and the beam runs in pulsed mode. The proton beam loading is too heavy to compensate for the PI feedback controller as the pulse length exceeds 50us. The accelerating field signal using only PI feedback control is illustrated in Fig. 9 and the compensated field taking both PI and feed-forward is illustrated in Fig. 10. The beam length is 150us and the accelerating gradient is 6.6MeV/m.

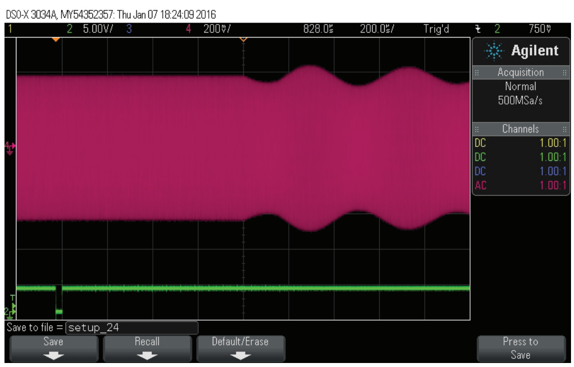

Figure 9: Cavity field with only feedback.

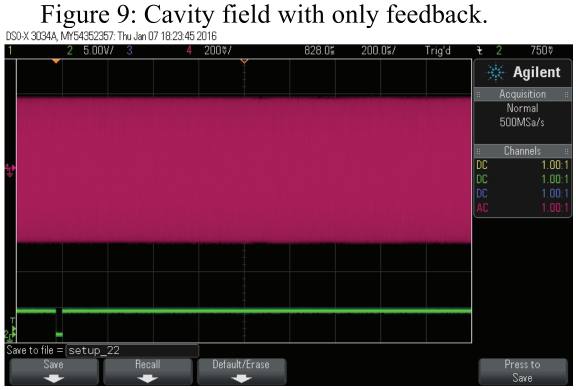

Figure 10: Cavity field with feedback and feedforward.

Software

Each cavity is controlled by a controller board and each controller board is supported by a single EPICS IOC server process. Fow now three IOCs run in the AMC CPU board Kontron AM5020 under Linux for the three controller board in each chassis as Fig. 11 shows.

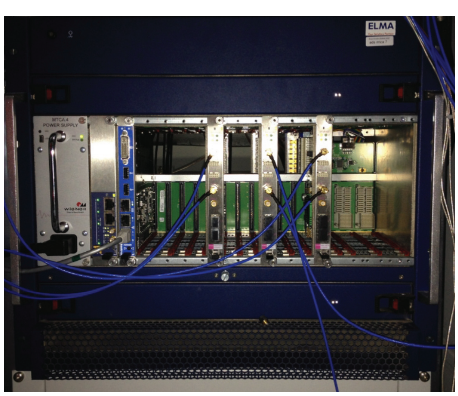

Figure 11: MicroTCA.4 chassis.

The operator interface (OPI) software is developed using CSS (Control System Studio). The typical OPI in the central room for one cavity is illustrated in Fig. 12 (left).

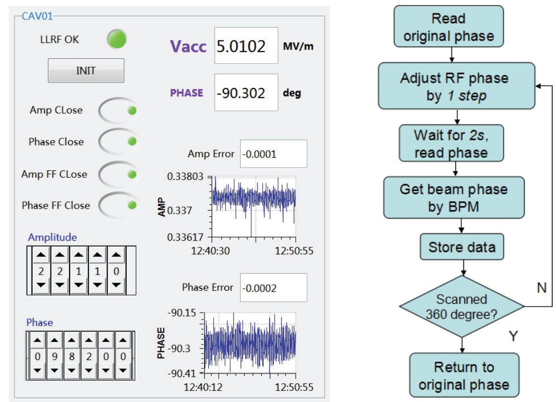

Figure 12: Operator interface for one cavity (left) and Flow of automatic phase scanning (right)

AUTOMATIC PHASE SCANNING

After power up of the LLRF system and the accelerator, the phase of all the cavities should be decided with the theoretical number. Automatic phase scanning function is developed base on the LLRF sytem and beam phase detection. The flow graphic is illustrated in Fig. 12 (right). The automatic script is writen in Python with Pyepics package supported. One round of phase scanning of one cavity takes about 5-20 minutes according to different phase step configurations and beam phase calculation time.

CONCLUSION

The MicroTCA.4-based LLRF system is developed and implemented for the C-ADS Injector I which satisfied the requirements of the spoke cavities and higher operations. The beam frequency=10Hz/beam current=10.6mA/beam length=1ms/beam energy=5.97MeV has been achieved after being accelerated by the first 7 cavities through Cryomodule I.

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