# DESIGN AND COMMISSIONING OF LLRF SYSTEM FOR ADS PROJECT IN CHINA *

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*Abstract*

The LLRF system for ADS Proton Linac injector I test facility built in IHEP consists of RF Reference system and LLRF controllers for one 325MHz RFQ cavity, two MEBT bunching cavities and 14 superconductive spoke cavities. This article describes the initial implementation of this system and the gradually improving. During the process of beam commissioning, we have accumulated practical experience and enhance the understanding of the system. This is a great help for future projects. Also we are gradually adding features for LLRF system to achieve practical application and stable operation, improve the availability.

## INTRODUCTION

The China ADS project has been established since 2011 under the cooperation between IHEP and IMP institutes of CAS. The whole commission process for ADS injector I has been separated into several steps.1$^{st}$ step is to achieve high average beam power at the exit of RFQ accelerator; 2$^{nd}$ step is to install test cryomodules with 2 low β superconductive spoke cavities and superconducting solenoid for hardware design verification and optimization. After that, 3$^{rd}$ step is to install CM1 and achieve 5MeV proton beam; 4$^{th}$ step is to connect two cryomodules to get 10MeV proton beam at the exit of the CM2. Up to now we have finished the 3$^{rd}$ round beam commissioning, and installed the CM2 in the tunnel for 4$^{th}$ commissioning round. After getting the stable operation of pulse proton beam for this SRF Linac, another cryomodules called CM4 will be integrated with 162.5MHz ADS injector II design by IMP and wish to achieve 25 MeV CW proton beam.

## LLRF SYSTEM

LLRF system itself is a distribution control system for large accelerator facility. Understanding of the plant to be controlled is the first thing for design this system, the hardware and software are the two important aspects. System availability becomes the most important goal from the view of top level design according the profound experience after several rounds of beam commissioning. Engineer care about the amplitude and phase stability the can achieve, what related parameters and methods they have to insure the stable running of the machine. When we are faced with frequent failure of the machine, how quickly recovery are also important considerations. In such circumstances, it is necessary to improve the automation of the system. Considering these factors, LLRF system not only needs to ensure stable operation of the accelerator, friendly interface, easy for users to handle the global situation of whole system.

### System Layout

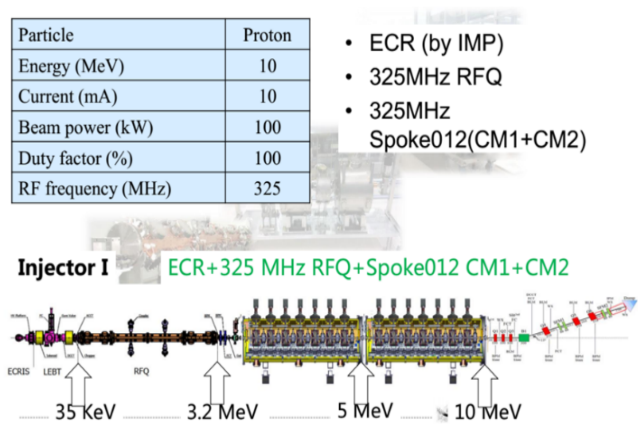


Figure 1: Layout of ADS proton Linac Injector I.

As shown in Figure 1, the injector I RF system consists of RFQ, MEBT bunching cavities and superconductive spoke cavities. The detail parameters for those RF cavities are listed on table 1, 2 and 3.

Table 1: Parameters of RFQ Cavity [1]

| Parameter | Number | Unit | Description |
|---|---|---|---|
| Frequency | 325 | MHz | |
| $Q_L$ | ~7000 | | *measured* |
| Injection energy | 35 | keV | |
| Output energy | 3.2 | MeV | |
| Beam current | 10 | mA | |
| Beam duty factory | 100% | | |
| Total power | 305 | kW | *Cavity power dissipation 273kW* |
| Beam transmission | 98.7% | | |

Table 2: Parameters of Buncher Cavity [2]

| | | | |
|---|---|---|---|
| Frequency | 325 | MHz | |
| $Q_L$ | ~12000 | | *measured* |
| Particle energy | 3.2 | MeV | |
| Beam current | 10 | mA | |
| Beam duty factory | 100% | | |
| Total power | 6.3 | kW | |
| Effective voltage | 120 | kV | |
| Tuner tuning range | 740 | kHz | |

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Table 3: Design Parameters of spoke012 Cavity [3] [4]

| Parameter | Number | Unit | *Description* |
|---|---|---|---|
| Operation frequency | 325 | MHz | |
| $\beta_0$ | 0.14 | | |
| $E_p/E_{acc}$ | ~5 | | |
| $Q_{ext}$ | $\sim 5\times10^5$ | kHz | |
| $R/Q$ | ~150 | | |
| $df/dp$ | +40 | Hz/mbar | |
| $df/dF$ | 60 | Hz/N | |

The Figure 2 shows the schematic of one typical RF station. The MO and REF. represent the Reference system for injector I. Each LLRF control unit includes the RF monitor unit, RF front end, mTCA.4 controller, tuner system and interlocks. Details of those units will be described in the following part.

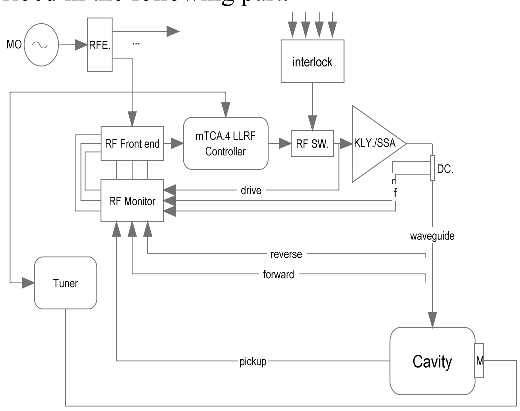


Figure 2: system schematic.

## *Reference System*

The ADS proton Linac injector I RF Reference System includes the master oscillator (MO) and Reference RF distribution systems. Coherent reference RF signals provide the ability to control the phase relationships between the fields in the front-end and the whole Linac RF cavity structures. We use Agilent E4438C signal generator as the MO, phase stabilized RF cable and one temperature compensated 32 ways splitter with low noise amplifier unit as the distribution system for RF station, Timing system and Beam instrumentations.

## *RF Signal Monitoring*

The RF monitoring signals in one typical system include the driver signals, forward and reflected waveform from the output of the amplifier transmitter, signals from the couplers at the accelerating structure entrance port and pickup signal from the cavity. Those signals are attenuated after splitters, matching network, and isolated for subsequent processing in RF Monitor unit.

## *RF Front End*

The RF Front End in one 19" chassis consists of an IQ modulator, IF up convertor, a local oscillator (LO), clock generation, and a multichannel down-converter. The Reference system with temperature compensated placed in the LLRF rack will provide a 325 MHz reference input signal to the RF Front End. In this unit, the reference signal is divided by 12.5 to result in the desired intermediate frequency (IF) of 26 MHz, which is then mixed with the 325 MHz reference signal. The extraction and amplification of the upper mixing product provides the required LO signal of 351 MHz around +7 dBm. Along the frequency divider chain the ADC and DAC clock signals of 104 MHz locked to the reference signal (325MHz divided by 3.125) are extracted. The 6-channel down-converters down-convert and amplify the 325MHz signals to an IF of 26 MHz with 5dB conversion gain. The vector modulator is designed as a baseband modulator to directly modulate the 325MHz reference signal, and the in-phase and quadrature input signals have to be DC-coupled. We keep on up convert channel to convert IF signal to 325MHz. Those units in one chassis are all temperature compensated with PID controller.

## *MTCA.4 Based LLRF Controller*

We adopt the mTCA.4 based platform (shown in Figure 3) as the baseband signal processing and LLRF control interface for ADS project at IHEP. The digital signal processing platform SIS8300 is based on the digitizer originally designed by DESY and license to struck innovative system company [5]. We choose SIS8900 at the first beginning as the RTM since not sure about the performance of underdamping method on the constructed system and use 4 times sampling method for IQ control algorithm on FPGA. Up to now we have implemented the control algorithms on that platform and put them into practical operation on injector I. We are also updating the firmware and features on the platform to satisfy new requirement from operation. The amplitude and phase stability of electrical field in accelerate structure can be achieved around 0.1° and 0.1% (both are rms value) during the 4th round of beam commission.

Figure 3: mTCA.4 platform.




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### *Tuner Controller*

We adopt one stepper motor with piezo actuators as the mechanical tuner for spoke cavity. The stepper motor has been used in a slow loop and the piezo in the fast. The comparator determines the exact actuator. 7 spoke cavities in cryomodules CM1 have been tested and we have taken the necessary measures to eliminate the impact of structural brought hysteresis for the slow tuning loop. This allows the superconducting cavity frequency tuning smoother and repetitive. The Lorenz Force detuning can be compensated by adopting piezo properly. Now another new 7 spoke cavities installed in CM2 in commissioning.

### *RF Interlock*

High availability interlocks and controls are required for the ADS high power RF stations. A module has been developed to process both fast and slow interlocks using CPLD logic to detect the interlock trip excursions. Modules can be chained together to accommodate as many inputs as needed. The vacuum Gate or contact signal of RF couplers or accelerate structure, ARC, temperature, water flow, tuner limiter etc.

### *Firmware， App. and GUI*

During the process of beam commissioning and implementing LLRF control system for Injector I, we have added some features such as SEL operation mode, automotive coupler and cavity conditioning, pulse or CW operation mode compatible, feedback with feedforward control method etc. for the firmware, still on the processing to be optimized.

The IOC for LLRF control system include the amplitude and phase loop, tuner loop, interlock loop and monitoring loops for power meter vacuum meters etc. Figure 4 and 5 (a), (b) shows the GUIs.

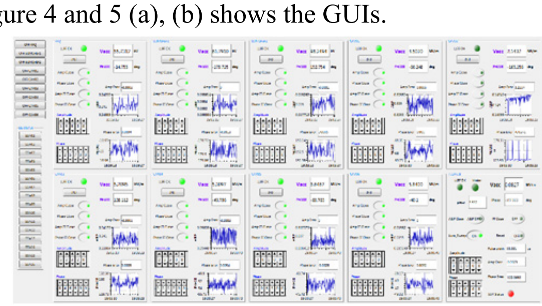
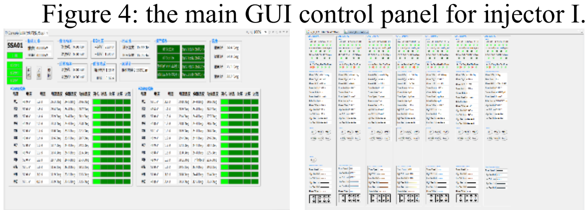


Figure 4: the main GUI control panel for injector I.



(a) (b)

Figure 5 (a) GUI for the SSAs (b) GUI for the tuner and interlock.

### *Future Work and Considerations*

With the addition of improved software and hardware, the LLRF control system for ADS proton Linac Injector I test facility at IHEP is becoming a full featured that is capable of supporting the conditioning and beam operation work of various that is needed to be done for ADS project. There are some research work be done during commissioning such as study the mechanical and electrical feature of spoke cavity, Lorenz forcing detuning compensation, beam loading effects and adaptive feedforward control etc. As always, we will discuss and cooperate in related fields, expect more suggestions.

## SUMMARY

The ADS Proton Linac injector I successfully achieved stable operation with 7 low-beta superconducting spoke cavities with high gradient on January 21st in 2015. The proton beam current was above 10.6 mA, the width of the pulsed beam was 1 millisecond, and the output energy reached about 6 MeV. The MicroTCA.4 Platform LLRF control system, which was the first time in China that this signal processing platform was applied to practical operation of a large accelerator facility. The 3$^{rd}$ round of beam commissioning showed the reliability of the LLRF in controlling the RFQ, MEBT bunching cavities and low-beta superconducting spoke cavities. It also guaranteed a smooth transfer for the beam commissioning mode from a narrow beam pulse mode to a continuous wave mode.

## ACKNOWLEDGMENT

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