Overview of the CSNS Linac LLRF and operational experiences during beam commissioning

Zhencheng Mu
Chinese Spallation Neutron Source (CSNS), Dongguan, China
Outline

- Introduction of CSNS Linac RF System
- Digital LLRF Control System
- Summary
Chinese Spallation Neutron Source (CSNS)

- Pulse Repetitive frequency: 25Hz
- Linac beam energy: 80MeV
- RCS beam energy: 1.6GeV
- Beam Power to Target: 100kW

- Linac is comprised of:
  - 1 RFQ
  - 2 Buncher Cavities
  - 4 DTL Accelerators
  - 1 Debuncher Cavity
Introduction of CSNS Linac RF System
Linac RF system owns three types of power sources

- RFQ: two 350kW 4616 tetrodes
- Bunchers/Debuncher Cavities: three 25kW solid state amplifiers
- 4 DTLs: four 3MW klystrons
Two Burle 4616 Tetrods Combined for RFQ

RF power requirements for RFQ:

<table>
<thead>
<tr>
<th>RF power</th>
<th>RF pulse width</th>
<th>Rep. rate</th>
<th>Duty factor</th>
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<tbody>
<tr>
<td>410 kW (cav. loss) +120 kW (beam loading) = 530 kW</td>
<td>650µs</td>
<td>25pps</td>
<td>1.625%</td>
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Each 4616 tetrode can output 350kW, \(2 \times 350kW = 700kW\). The power source was used in the RFQ beam commissioning in 2015, it works well!
Three Solid State Amplifiers for Two MEBT Buncher Cavities, One LRBT Debuncher Cavity

- Each solid state RF amplifier can output 25kW power, redundancy design, test results show that these amplifiers have excellent performance and stability.

800W power amplification module

Three-stage power combiner

800W power module array

Two 25kW solid state amplifiers

input-output linearity of the 800W module
Four Klystrons for Four DTLs

- CPI 324MHz pulsed klystron amplifier, Maximum output power: 3MW. The installation and commissioning of the first klystron power source have been finished.

Block diagram of the klystron power source.

- 120kV serial resonant high voltage power supply
- IGBT solid state switch modulator
- Crowbar: ignitron as the energy relief device
Digital
LLRF Control System
Duties of the LLRF system

- ±1% amplitude of the cavity field
- ±1° phase of the cavity field
- Cavity resonant frequency control
- High Power protection
The 324MHz Reference Line

— The reference line is located in sub-tunnel, frequency of the reference signal is 324MHz.

— the Andrew phase stable cable is wrapped in a constant temperature water jacket, the variation range of the water temperature limited within $\pm 0.1^\circ$.

— The reference signal is picked up through a Narda 3000 coupler, Andrew phase stable cable to each station.
The Analog Module

- The analog module consists of two units:
  - The analog up-down conversion unit: RF 324MHz, LO 360MHz, IF 36MHz.
    - 4× down conversion channels
    - 2× up conversion channels
  - The clock generation unit
    - 144MHz, 36MHz, 72MHz

- Put two units into a temperature stabilizing chamber, air cooling semiconductor refrigeration, the temperature variation range is kept within ±0.1°.
The Digital Field Control Module

- **Hardware**
  - 1 × FPGA: Altera Stratix II family EP2S90F1020
  - 2 × ADCs with 4 sampling channels: Linear LTC2156, 170Msps 14-bit, DDR LVDS output to FPGA.
  - 2 × DSPs: TI C6713

- **ADCs Sampling frequency** 144MHz, IF 36MHz, quadruple frequency sampling gets I, Q, -I, -Q……
  - 3 IF signals are sampled by ADCs: cavity field, forward, previous cavity field.
  - Phase difference between the forward signal and the cavity field is used in the tuning system.
  - Previous cavity field is used to recover the working point if something changed in the previous RF system.
Software: IQ Demodulation → Feedback PI Controller → Feedforward Table → Numerically Controlled Oscillator (NCO).

— Feedback Loop: Suppress various disturbances (power sources noises, high voltage drop, beam loading, etc).

— Feedforward: It compensates the beam loading, triggered by beam gate, fixed value table.

— NCO: Output 36MHz IF, digital frequency conversion technology.
In June 2015, good stability of the RF field has been achieved about $\pm 0.4\%$ in amplitude and $\pm 0.5^\circ$ in phase during the RFQ beam commissioning, the pulse width of the RF is 700$\mu$s, beam width 500$\mu$s, beam intensity 10mA.

Owing to the beam dump limitation, DTL just ran with low beam duty, maximum repetitive frequency 5Hz, and the beam pulse width 200$\mu$s.
The Digital Frequency Conversion Technology

- Digital Frequency Conversion Technology
  - Target: the power source output frequency automatically tracks cold cavity resonant frequency, less reflected power.
  - Actuator: NCO

- Two mode can be selected
  - Manual mode
  - Auto mode: the detuning frequency $\Delta \omega$ from the operating frequency of the cavity by the phase curve of the cavity field during the field decay.

Frequency sweeping dynamic range is about $\pm 1$MHz.
The Tunner Loop

- Two methods to judge whether the cavity is close to resonant state or not.
  - The phase difference between the cavity input and output signal.
  - The detuning frequency $\Delta \omega$ which is directly calculated from the phase curve of the cavity field during the field decay.

- Actuator
  - RFQ: Cooling water, regulate the input cooling water valve
  - Buncher/Debuncher cavities and DTL: Tunner

- We use the detuning frequency $\Delta \omega$ to operating the actuator, higher precision.
  - The servo motor moves to maintain the cavity resonant.
  - Displacement sensor sends turner displacement information to IPC using TCP/IP protocol.
The High Power Protection

- Power monitor
- Eight channels ADCs
- VSWR, count the VSWR protection number.
- Test result shows the RF shutdown time is less than 460ns once VSWR protection.

- AFT ARC sensor and the sentry.
- Klystron output window, Circulator, Cavities, etc…
- Count ARC number
Summary

— Two linear power supplies of the LLRF cabinet are ever broken, we need more time to decide if we should change them all.

— Long term stability of the LLRF system need time to test.

— In the future, we want to improve this system with chassis and CPU, maybe cPCI, vxworks OS.
Thank you!!