RF SYSTEM OF THE CSNS SYNCHROTRON

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Abstract

The accelerator of China Spallation Neutron Source (CSNS) consists of a H− linac and a rapid cycling synchrotron (RCS). The protons injected into the RCS will be accelerated from 81MeV to 1.6GeV by the RCS RF system providing a maximum accelerating voltage of 165kV. The RF frequency sweeps from 1.02 MHz to 2.44 MHz with a repetition rate of 25Hz. The ferrite-loaded RF cavities will be used in the RCS RF system. Each cavity has own RF power tube amplifier, bias current supply and full digital LLRF control loops. The R&D of RCS RF system have been completed, it compose of the prototypes of a full size ferrite loaded RF cavity, a high power tetrode amplifier, a switching type bias supply of 3000A and a full digital embedded controller of LLRF. CSNS RCS RF system design and the test results of the R&D prototype will be described in this paper.

INTRODUCTION

The CSNS synchrotron is a rapid cycling proton synchrotron with a circumference of 229.7m. The purpose of the RCS RF system is to capture and accelerate the protons injected into the ring, then extract the beam at the end of an accelerating cycle of 20ms. The synchrotron beam energy is from injection energy of 81MeV to extraction energy of 1.6GeV. RCS RF system is designed to adopt 8 ferrite-loaded RF cavities, including one spare cavity, to provide a peak RF voltage of 165kV with a frequency swing of 1.02 to 2.44MHz and a synchronous phase swing of 0º to 45.3º for operation on harmonic h=2, as shown in Fig.1 [1]. Table 1. summarizes the main machine parameters related to the RCS RF system.

CAVITY AND POWER AMPLIFIER

The RF cavity used in RCS is a ferrite-loaded coaxial resonator with 2 accelerating gaps and single ended (see Fig. 2). Ferrite loaded material is Ferroxcube 4M2. There are 56 ferrite cores, with the inner and outer diameters of 25cm and 50cm respectively, installed in a cavity, each gap holds 28 pieces and each core is 2.5cm thick. Between two ferrite cores insert a copper cooling plate with a thickness of 6.7mm, it is made from dual rectangular copper conductor winding in a spiral shape. The cross section of water flowing is 9*4mm^2, and the water velocity is less than 1.8m/s. The cavity total length is about 2.7m, and ferrite length is 1.4m. The gap inductance can be shifted as a bias field altering from 8.1μH to 1.4μH，the required permeability is μ_r=83~14.6, corresponding to bias current varying range of 230~2800A. The resonant frequency of the cavity can sweep within 1.02~2.44MHz with cavity gap capacitance of 3nF to satisfy the CSNS RCS operation. A nominal peak RF gap voltage of more than 10.3kV is required. The maximum RF magnetic flux density B_{rf} is near 186Gs around 1.4MHz.

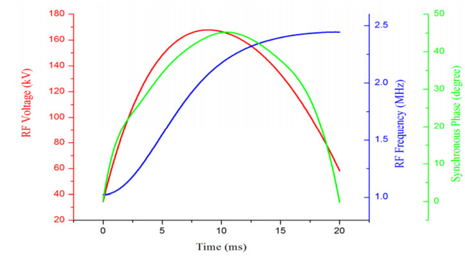

Figure 1: RCS RF voltage, synchronous phase and RF frequency patterns during accelerating time of 20ms.

Table 1. RF Machine Parameters for CSNS RCS: [2]

Parameters	Value
Beam power (kW)	100
Circumference (m)	229.7
Energy (GeV)	0.081~1.6
Intensity (ppp)	1.56E13
Circulating dc current (A)	1.5/ 3.5
Repetition rate (Hz)	25
Harmonic number	2
RF frequency (MHz)	1.02~2.44
Peak RF voltage (kV)	165 (h=2)

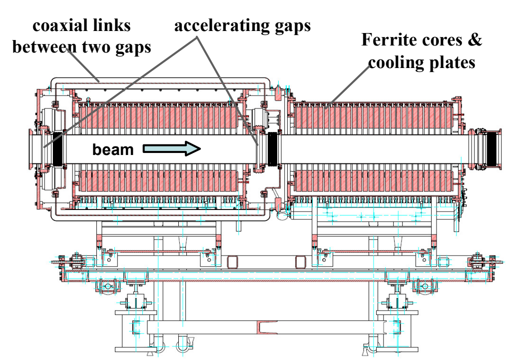

Figure 2: CSNS RCS RF cavity

The two RF gaps of cavity are interconnected in parallel via two links and driven by a tube power amplifier adjacent to the cavity. An undesired resonance with higher order parasitic mode of 7.6MHz, which leads the waveform of cavity voltage happen distortion due to a larger fourth harmonic component of the fundamental RF frequency of about 1.9MHz, had been observed on the cavity prototype. It can be found on the cavity voltage waveform in figure 8. It is caused by the

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distributed inductance of cavity gap links and gap capacitors. In a new cavity design we improved the shape and size of gap links from circular coaxial to rectangular coaxial to reduce its distributed inductance and economize the volume of RF cavity. The dimension of a rectangular coaxial link is outer conductor of 21*6.4cm, and inner conductor of 15*0.4cm. The result of calculation by the CST code shows the cavity parasitical resonance could be moved up from 7.6MHz to 10MHz, just out of the 4th harmonic range of maximum RF fundamental frequency of 9.76MHz.

The RF power amplifier consists of a three stage amplifiers chain (see Fig. 3). The final stage amplifier using a tetrode TH558 operated in class AB1, with a configuration of cathode-grounded. The maximum plate dissipation of the tube is 500kW. The main amplifier is driven by a feedback (FB) amplifier of 800W located in the rack of final stage amplifier adjacent to the cavity. It is composed of two stage tetrode amplifiers employing 3 tubes of FU-100F, which two tubes were parallel connected as the FB amplifier output and driven by a tube (see Fig.4). In order to match the impedance between the output circuit of FB amplifier and the input circuit of final stage tube, an impedance match network of 4:1 is used to convert the impedance from 800Ω in FB amplifier output side to 200Ω in the grid input side .The total gain of FB amplifier is around 38dB. Because of the RF cavity operation in a sweeping mode, the reactance of the final stage tube input circuit capacitances should be compensated by an adjustable inductance of ferrite-loaded, that is a tuned low-Q resonant circuit and controlled by a closed grid tuning loop, the inductance varying as a bias current to keep the input voltage and output of the FB amplifier in phase during RF frequency sweeping. The grid tuning control function is realized by FPGA programming [3]. The gain of the final stage amplifier is about 30dB. The RF drive signal from a wide-band preamplifier (SSA) of 500W will be combined with a RF voltage signal extracted from the cavity which having a proper amplitude and delay to drive FB amplifier, forming a RF direct feedback around the power amplifier to reduce the cavity impedance seen by the RF amplifier [4]. The RF feedback loop gain of 20dB has been achieved in the experiment of the RF system prototypes. The impedance seen by the beam could be reduced 10 times probably. It is benefit for the beam loading compensation.

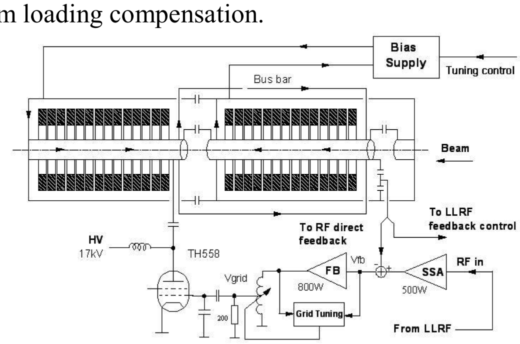

Figure 3: CSNS RCS RF system simplified schematic

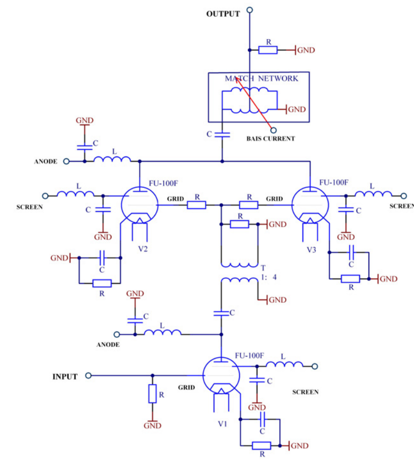

Figure 4: Schematic circuit diagram of FB amplifier

LOW LEVEL RF SYSTEM

The main task of RCS LLRF control system is to regulate the RF voltage amplitude, frequency and phase of the ferrite-loaded cavity following the RF operation patterns required by the physicist to accelerate proton beam and minimize the beam loss. RCS LLRF system will use a full digital embedded control system to accomplish the various control functions and maintaining the RF system stability synchronously, such as precise RF signal generation based on DDS, cavity voltage and dynamic tuning feedback with an accessorial cycle by cycle adaptive feed-forward control, and the tube grid tuning control, synchronous phase of RF voltage vs. beam and orbit radial control, and feed-forward beam loading compensation, and so on. All functions of the control loops are realized by FPGA programming. [4]

A prototype of full digital embedded control system based on cPCI bus has been developed successfully. It consists of a CPU main card of CPCI- 6020 with a 500 MHz MPC7410 processor and running the VxWorks operating system, a 6U cPCI bus crate, and 6U FPGA control boards developed specially for RCS LLRF. We adopt a FPGA chip of Altera Stritax III EP3SL150 with embedded DSP blocks and a soft CPU core of Nios II. The FPGA boards have four fast 16bit ADCs to sample the cavity voltage, grid voltage, input voltage of FB amplifier and beam FCT signals at a rate of 40MHz respectively, and two fast 14bit DACs for RF drive voltage, two FDIs (Fiber Data Interface) to drive cavity and grid tuning bias current supply through fiber cables, and some IO ports for the fast interlock system. The RCS LLRF control system is EPICS-based. EPICS drivers and device support for CPCI-6020 CPU card and the FPGA digital boards were developed and tested successfully. The configuration of RCS LLRF system is shown in figure 5. The digital I/O boards and control loops are discussed in detail in [3].

Each cavity has own RF power source, bias supply and individual LLRF control loops. So in a unit of the ring RF embedded control systems a CPU board of

CPCI-6020 needs to manage 8 digital I/O boards, one board for one cavity. Host computer can control data transmission with LLRF system in the central control room, such as downloading function tables and control parameters and uploading history data consists of interesting waveforms.

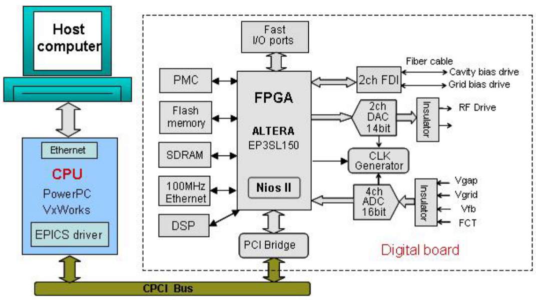

Figure 5: RCS embedded LLRF system configuration

RF SYSTEM TEST RESULTS

The R&D prototype of RCS RF system have been developed, including a full size ferrite-loaded RF cavity, a set of RF power tube amplifier, 3kA bias current supply and digital LLRF system, see figure 6 and 7. The high power integration test of RF system was completed with the cavity amplitude loop, cavity tuning loop and grid tuning loop all closed. The RF direct feedback loop was turned on also with a closed loop gain of 20dB. All RF equipments operated well stably. The maximum cavity gap voltage can reach to more than 10.3kV during 20ms sweeping operation, the RF frequency sweep from 1.022~2.44MHz. Figure 8 shows the sweeping voltage waveforms of the cavity gap and tube grid. The gap voltage error was less than ±1%, RF system detuning angle within ±5 degree except the beginning of system sweeping with a lager detuning angle of ~±10º.

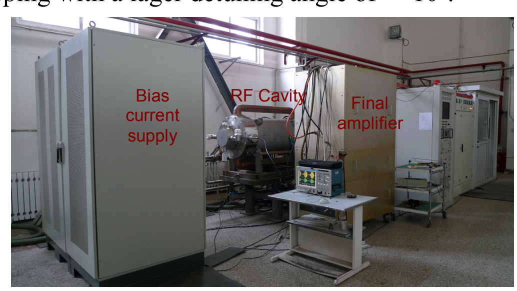

Figure 6: View of the CSNS RCS RF system prototypes

Figure 7: Digital LLRF control system prototype

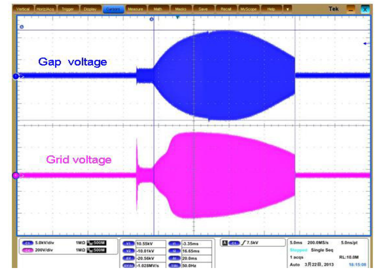

Figure 8: Waveforms of the cavity gap and tube grid operated in sweeping mode with repetition rate of 25Hz.

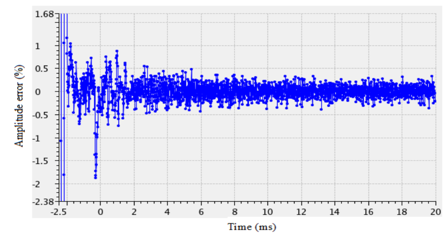

Figure 9: Cavity gap voltage amplitude error within a cycle of 20ms.

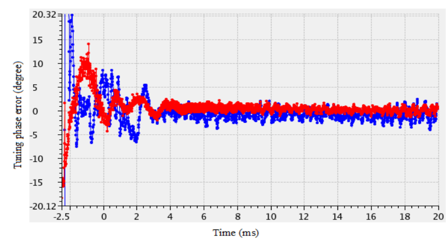

Figure 10: Cavity detuning angle (blue) and Grid tuning error (red) within a cycle of 20ms

CONCLUSION

A set of CSNS R&D prototypes of RF cavity and its power amplifiers, bias supply, and full digital LLRF system has been developed and passed high power test successfully. The main performances of prototypes meet the demands of CSNS RCS RF system. The improvement design of ring RF equipments for the batch production has been completed. The fabrication of whole 8 sets of RF cavities, power amplifiers and bias supplies is under way.

REFERENCES

[1] CSNS physics group provide.
[2] CSNS primary design report.
[3] X. Li, "Overview of the CSNS/RCS LLRF Control System", in this conference.
[4] D. Boussard, "Control of Cavity with High Beam Loading", IEEE, TNS, Vol. NS-32, No.5, pg 1852, October 1985.

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