Design of the LLRF control system for MA cavity at CSNS RCS

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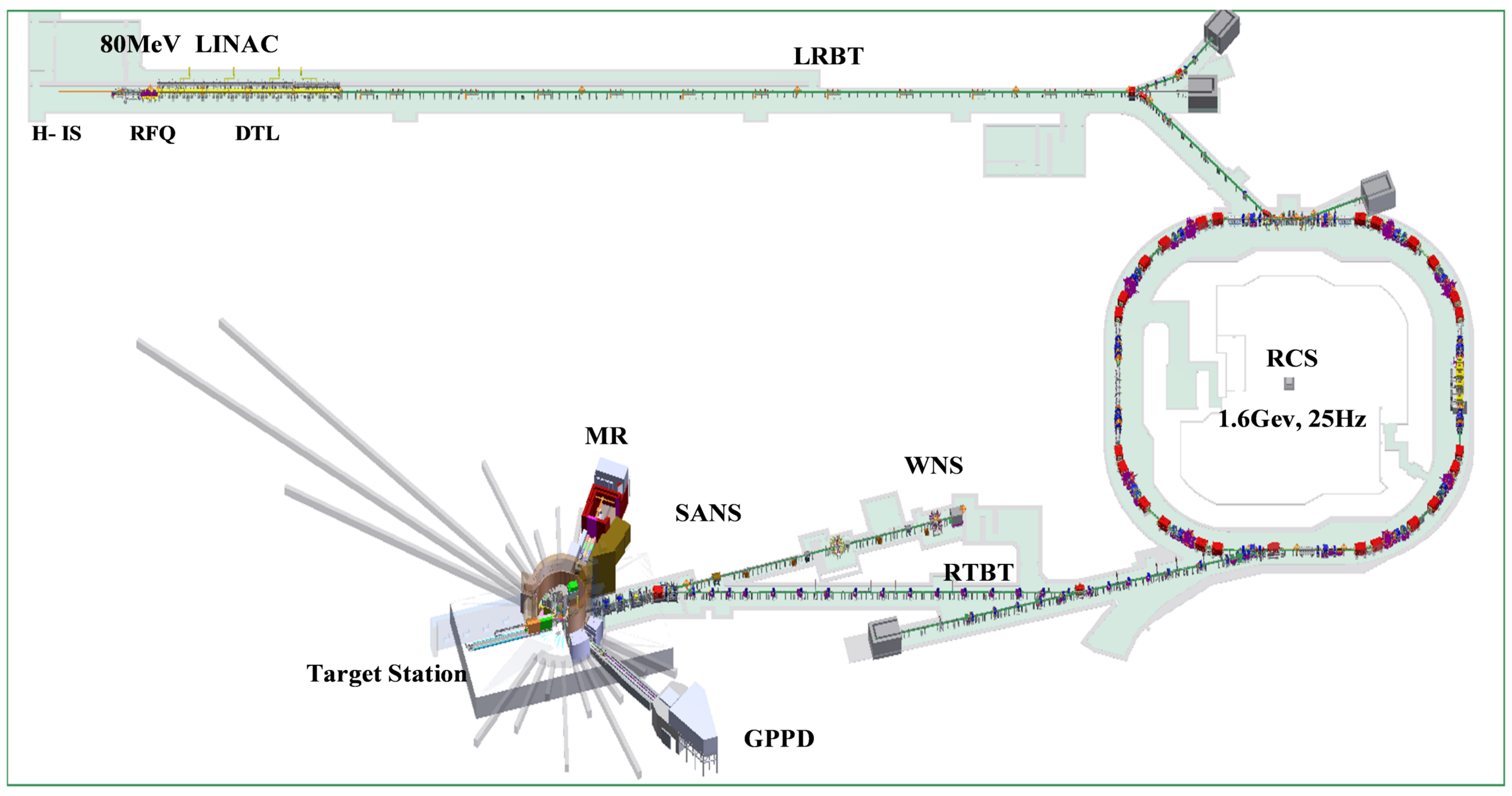
• Introduction

The China Spallation Neutron Source (CSNS) is a large-scale scientific facility for neutron science, and it also provides a powerful platform for multidisciplinary application research. it consists of an 80MeV H− linac, a 1.6-GeV rapid cycling synchrotron (RCS), a target station, linac to ring beam transport line and ring to target beam transport line. The beam power was successfully reached 125 kW with a low beam loss in February 2022.



■ Figure 1. schematic layout of CSNS

In order to increase beam power, during the summer in 2022, we employ magnetic-alloy (MA) cavity in the rapid cycling synchrotron (RCS). It is a wideband cavity (Q=2), allows the second harmonic rf (h= 4) operation, with the existing ferrite cavity to realize the dual-harmonic acceleration. The second harmonic (h=4) is used for the bunch shape control and alleviating the space charge effects.

□Table 1: The main parameters of RCS

Circumference	227.92 m
Energy	0.08-1.6GeV
Repetition	25Hz
Number of cavities	8 ferrite cavities 1 MA cavity
Number of gaps	2/3
Fundamental RF frequency	1.02-2.44MHz
Harmonic number	2/4
Maximum RF voltage	180/50 kV

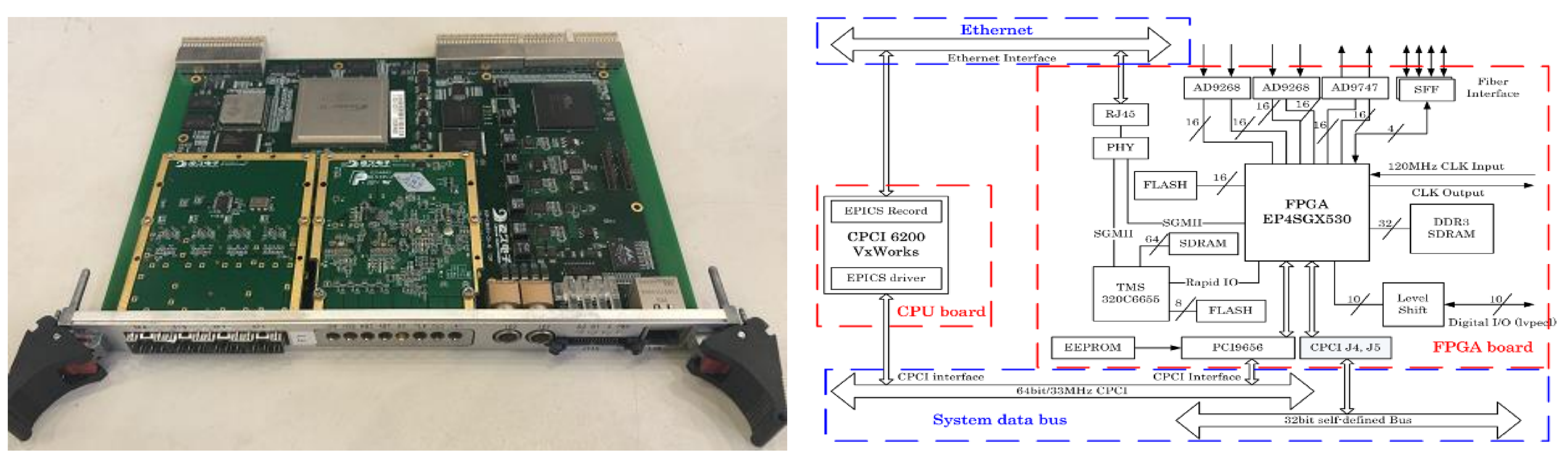
•LLRF control system hardware

The hardware platform includes a CPCI6200 CPU board, a standard timing board, eight FPGA boards to realize eight ferrite cavities control, a FPGA board to realize magnetic-alloy cavity control, and four beam signal processing boards.

I. CPU board: with EPICS IOC to realize control parameters setting and system status monitoring
II. Timing board : to receive a global 25Hz timing signal and generation of event trigger. such as the extraction trigger and the linac chopper pulse
III. FPGA board : to realize RF signal digitization data processing and control arithmetic for control function
IV. Beam signal processing board : to realize FCT, WCM, BPM data processing
V. Self-define bus : based on LVDS is adopted to transmit beam signal

■ Figure 3. Photograph of the LLRF control system and self-define bus

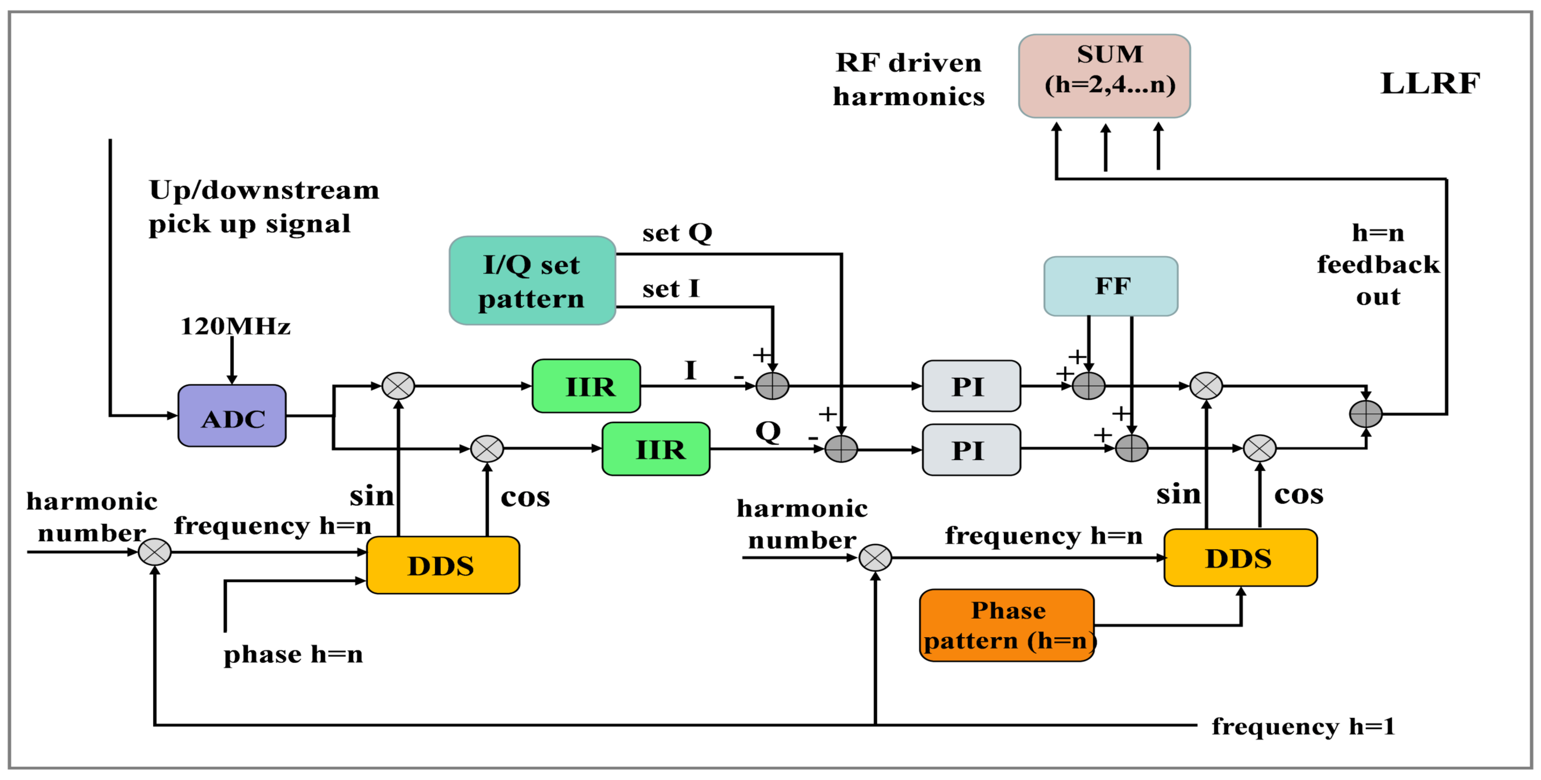
The LLRF control system is a full-digital system, the FPGA board is the heart of the LLRF control system, it has a StratixIV FPGA (EP4SGX530), four high-speed analog-to-digital converters (ADC) and two digital-to-analog converters(DAC), 8-bit digital I/O,SDRAM, optical interface, ethernet interface, and so on.



■ Figure 4. Photograph of the FPGA board and LLRF control system interface

• The multi-harmonic feedback control

The cavity gap voltage converted to pick up signal, pick up signal is directly digitized by ADCs operating at a clock frequency of 120 MHz. The sine and cosine signals for the I/Q demodulator and modulator are generated by a direct digital synthesizer(DDS).The phase pattern is obtained from the I/Q modulator to the demodulator, calibration the loop phase is necessary to I/Q control loop stability. The frequency signal (h=n) fed to the DDS is obtained by multiplying the revolution frequency (h=1) by the selected harmonic number. A 100 kHz bandwidth IIR low pass filter is used to obtained the in-phase and quadrature-phase (I/Q) values. The acquisition I/Q values is compared to the I/Q set pattern are I/Q error. I/Q error fed to PI controller and the I/Q modulator, the feedback output signal is generated. All the feedback signals are summed up to the RF driven signal, finally, the driving signal is generated by DACs.

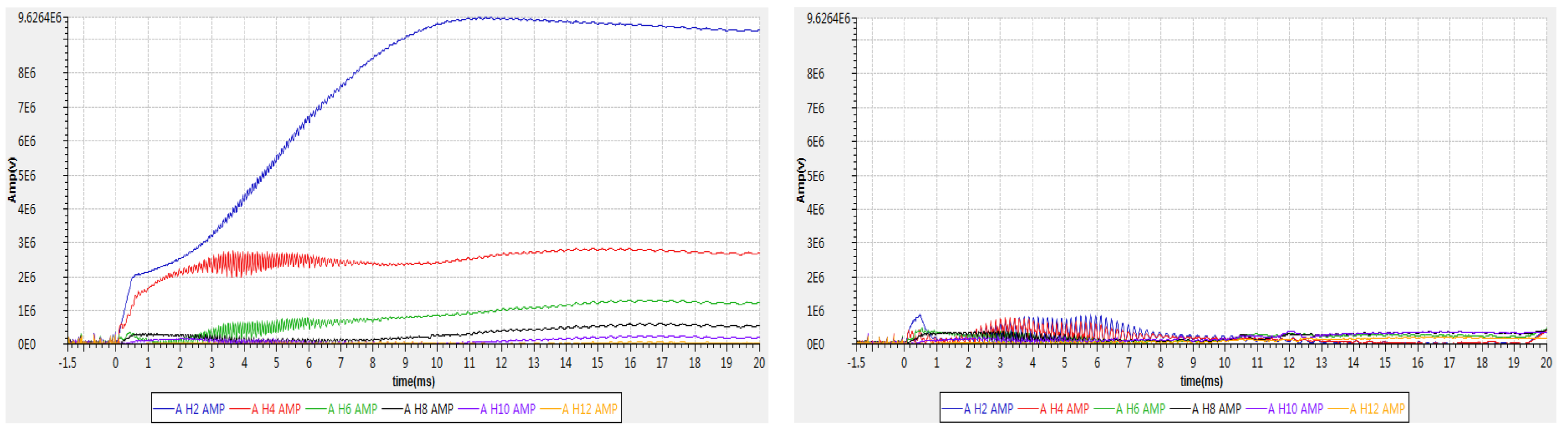


■ Figure 5. The block diagram of the multi-harmonic feedback control

•Test results

□ Beam loading compensation test without rf drive

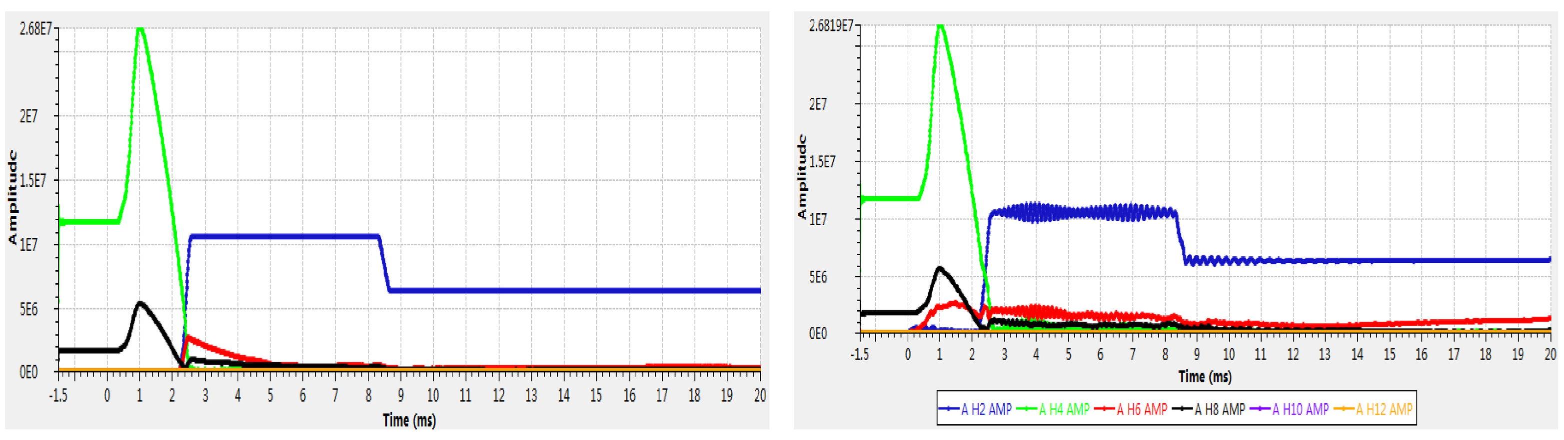
The test for beam loading compensation was conducted during the summer in 2022, in the case with beam commissioning, without RF driving signal, acceleration of two bunches the maximum beam intensity is 1.95×10^13 ppp, only even harmonics are observed in the gap voltage, the maximum wake voltage values (h = 2,4,6,8) are about 10kV, 3kV, 1kV, 0.5kV. When feedback control loop (h=2, 4, 6) are closed with the set points (Iset, Qset) set to (0, 0) , all wake voltages are suppressed to less than 0.5kV , h = 8 is less than 0.5 kV, so h=8 feedback control loop is not used.



■ Figure 6. The wake voltage in MA cavity (left) and the beanm loading compensation test (right)

□ With beam commissioning for dual-harmonic acceleration with rf drive

Eight ferrite cavities are provide the fundamental RF voltage, from injection to 2.1ms, MA cavity provides the second harmonic RF voltage is used for dual-harmonic acceleration and from 2.1ms to extraction, MA cavity provides the fundamental RF voltage is used to reduce the beam loss in the arc region. A single shot mode is used for the test, beam intensity is up to 1.95×10^13 ppp, corresponds to acceleration of a 140 kW beam at a repetition rate of 25 Hz . Figure 7 shows the harmonic components of the voltage when feedback for (h=2, 4) are closed.



■ Figure 7. The harmonic components of the voltage without the beam(left) and with an acceleration of a 140kW beam(right)

•Summary

We design of the low-level RF(LLRF) control system for the wideband MA cavity, it is a full-digital system, the FPGA board is the heart. We describe the MA cavity multi-harmonic feedback control design , MA cavity is provides the second harmonic RF voltage, with the existing ferrite cavity to realize the dual-harmonic acceleration.Without beam was tested for the beam loading compensation,and with an acceleration of a 140 kW beam was also tested. The experimental results have confirmed the multi-harmonic feedback control works well.