DLLRF AND BEAM TRIP ANALYSIS IN THE STORAGE RING OF SSRF

X. Zheng[1,2], Y.B. Zhao[1,2], H.T. Hou[1,2,3], Z.G. Zhang[1,2,3], S.J. Zhao[1,2], Z. Li[1,2], C. Luo[1,2], Z.Q. Feng[1,2], D.Q. Mao[1,2], J.F. Liu[1,2]

[1]Shanghai Institute of Applied Physics, CAS, Shanghai, P.R.China
[2]Shanghai Key Laboratory of Cryogenics & Superconducting RF Technology, Shanghai, P.R.China
[3]Graduate University of Chinese Academy of Sciences, Beijing, P.R.China.

Abstract

The digital low level radio frequency (DLLRF) system and the beam trip diagnostic system in the storage ring of Shanghai Synchrotron Radiation Facility (SSRF) have been operational for more than one year. The DLLRF has successfully maintained the amplitude and phase stability of the cavity field in the superconducting cavity even when the beam current in the storage ring reached 300mA at 3.5GeV, and the beam trip diagnostic system has been realized and is helpful for improving the reliability of the RF system.

INTRODUCTION

Superconducting RF (SRF) modules are adopted in the storage ring of Shanghai Synchrotron Radiation Facility (SSRF) to compensate the beam current for the power losses [1-2]. The high stability and precision of the RF voltage in the SRF cavities, as well as better diagnostics and maintenance, drives the development of low level radio frequency (LLRF) systems [3] and beam trip diagnostic system [4]. LLRF can stabilize the RF voltages in the SRF cavity via feedback loops and thus improve the accelerator performance. The digital LLRF (DLLRF) controller [5] used in the storage ring of SSRF contains an amplitude loop, a phase loop and a tune loop. The precision over a long time is better than 28Hz for the tune loop, better than ±1% for the amplitude loop and better than ±1 degree for the phase loop. The beam trip diagnostics [6] can distinguish the first fault correctly from various causes of beam trip and is helpful in the improvement of the reliability of the SRF system.

DIGITAL LOW LEVEL RF

With the development of integrated circuit, it is optional to build up LLRF with digital technology, i.e., digital LLRF (DLLRF) which has many advantages over traditional analogue LLRF in accuracy, stability and remote control [7]. The general layout of the DLLRF system used in the storage ring of SSRF is shown in Fig.1. The reference signal provided by a signal generator, Agilent 8663B, is divided into three parts and sent to each DLLRF controller respectively. Besides the reference, the forward signal from waveguide and the cavity signal from the pick-up are also input into the controller through the analog front end. The RF output signal from the controller is sent to the klystron. The local PC of each LLRF station communicates with its corresponding LLRF controller through TCP-IP protocol, and its communication with center room is realized by the Share-memory.

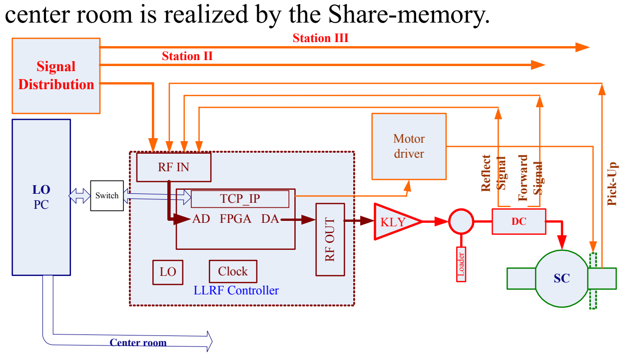

Fig. 1: General Layout of DLLRF in the Storage Ring of SSRF

The LLRF controller consists of several features as shown in Fig.2: local oscillator (LO) signal generation, clock signal distribution, RF up/down conversion and digital signal processing (DSP). The LO signal is obtained by mixing the reference signal with the 38.4MHz signal generated by a commercial direct digital synthesizer (DDS), AD9858. The clock signal distribution, containing a 30.72MHz clock for analog-to-digital convert (ADC) and a 122.88MHz clock for digital-to-analog convert (DAC), is built up based on another commercial board AD9510, of which the 38.4MHz clock generated by DDS is served as the reference clock. The RF down conversion is to use a LO and a mixer to down-convert the signal to an intermediate frequency (IF), while the RF up conversion is to use a LO and a mixer to up-convert the processed IF signal to the origin signal frequency. The DSP is realized through an FPGA, Alter Stratix II EP2S60. The field control and tune loop algorithm are all done in the FPGA. This FPGA also provide the interface communicating with the local PC and the signal for driving the step motor.

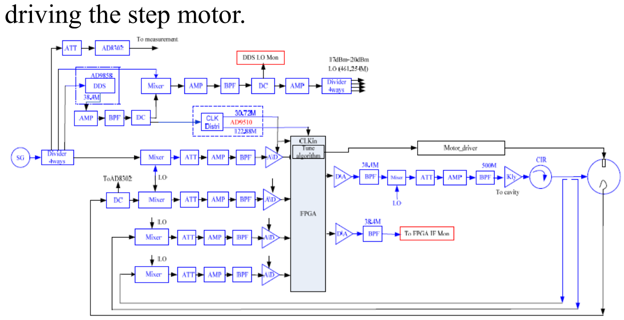

Fig. 2: Design sketch of the LLRF controller

The total responsive time of the field feedback loop is 770 μs , and the response time of the LLRF controller, i.e., the interval between the instant at which a signal enters the analog front end and the instant at which the first character of the response is sent from the RF output end, is 660ns. The long-term stability of phase and amplitude is measured and the result is showed in Fig.3. The variations of the amplitude and phase are less than $\pm 1\%$ and $\pm 1^o$, respectively.

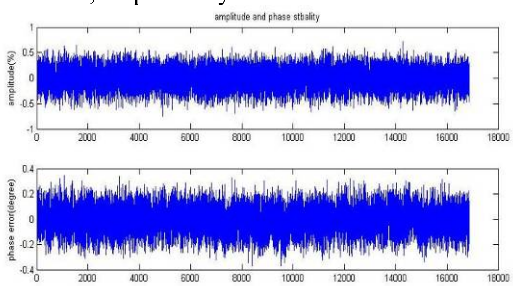

Fig. 3: Long-term stability

The LLRF also has the ability to modulate the amplitude and phase of the forward RF power, and satisfies the needs of conditioning the SRF cavities and windows. The conditioning of the superconducting cavities at SSRF were carried out without beam firstly and then with beam. The conditioning of the superconducting cavities at SSRF were carried out without beam firstly and then with beam. The conditioning without beam is to change the frequency of forward power to be 15kHz away from the resonance frequency, thus making total forward power be reflected back. The out-gassing as shown in Fig.4 appears at forward power levels of about 60kW.

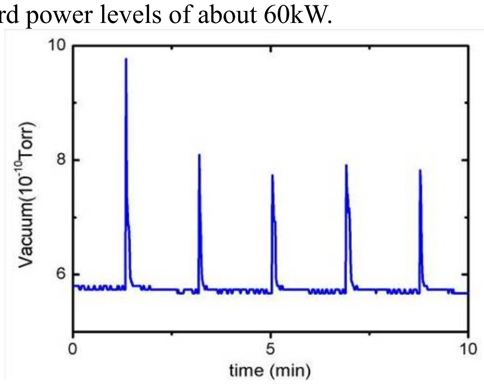

Fig. 4: Outgassing near RF window,15kHz off resonance

The conditioning was then carried out with 200mA beam current with the assistance of LLRF. In order to ensure every cavity was able to deliver enough power to the beam, one cavity was fully conditioned at a time through carefully adjust the acceleration phases of three cavities. Here the cavity at position #1 is taken as an example. The conditioning progress of this cavity encountered vacuum burst at power levels of about 156 kW. As shown in Fig.5, continuous vacuum bursts happened around RF window when conditioning with 200mA beam current. By carefully adjust the amplitude and acceleration phase of the RF field in this cavity through LLRF controller, such bursts last for several hours without vacuum interlock, and the forward power of cavities is conditioned from 156kW to 167kW. In spite of such full conditioning, the vacuum burst near the RF window still happened and caused a beam trip on vacuum interlock when the forward power was up to a lower power range such as 120kW. More time to condition thoroughly is still needed for the RF windows.

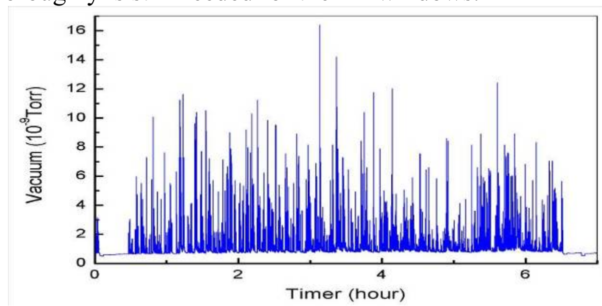

Fig. 5: Continuous vacuum bursts around RF window

BEAM TRIP DIAGNOSTICS

The beam trip diagnostic system is built up by taking advantage of a Dimension 4i recorder, which supports a maximum of 16 channels and whose maximum sampling rate is 200kS/s. This system has been successfully applied to clarify the resulting causes of beam trips. Some real scenarios are summarized in the following to demonstrate the usage of this diagnostic tool.

There are hundreds of machine protection signals (MPS) [8] requiring the beam kick-off, such as the temperature of the insertion devices or the vacuum chamber in the storage ring, etc. These signals are input to the interlock system of the Thomson amplifier, shutting down the output power from klystron, i.e., the cavity incident power. It is shown from Fig.6 that the cavity incident power is firstly dropped to zero, resulting in damping fluctuation of the cavity voltage and the cavity reflected power.

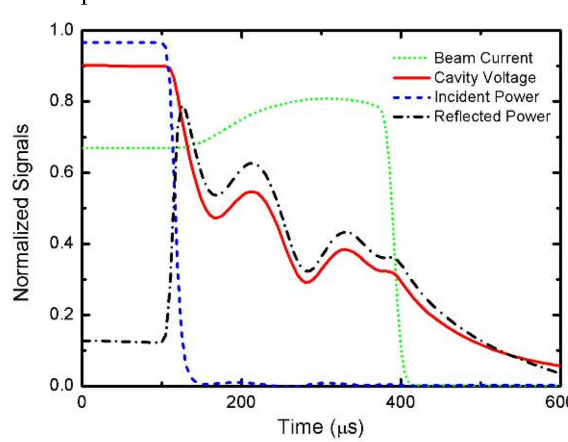

Fig. 6: Beam trip by MPS

An Orbit interlock signal will be generated when the beam deviates from the safe orbit. Fig.7 shows that the detected beam current is firstly decayed when some fault which causes the beam orbit deviation happens on a quadrupole magnet.

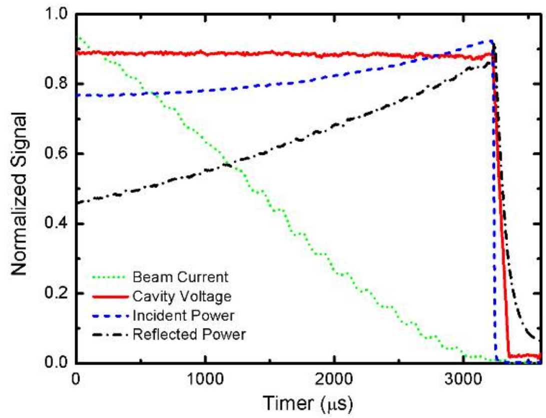

Fig. 7: Beam trip by Orbit interlock

Fig.8 shows a scenario that the cavity voltage is firstly dropped, while an interlock signal of the cavity reflected power is indicated in the interlock system of the Thomson amplifier. It is believed that some arcing may happens in the RF power couple region, dropping the cavity voltage, causing the reflected power greatly raised and thus making an interlock generation. The negative part means that the induced cavity voltage decelerating the beam is dominant.

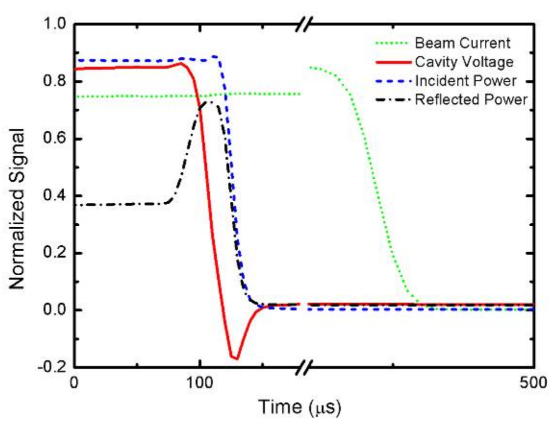

Fig. 8 Beam trip by interlock of cavity reflected power

Fig.9 shows the beam trip caused by a cavity quench signal. However, there was no temperature increment on niobium cavity and no pressure increment in helium vessel, indicating that no significant RF power has been absorbed by the cavity wall. It is believed that this quench signal is generated due to the fluctuation of cavity voltage that fulfilled the logic condition of the quench detector, rather than a real quench.

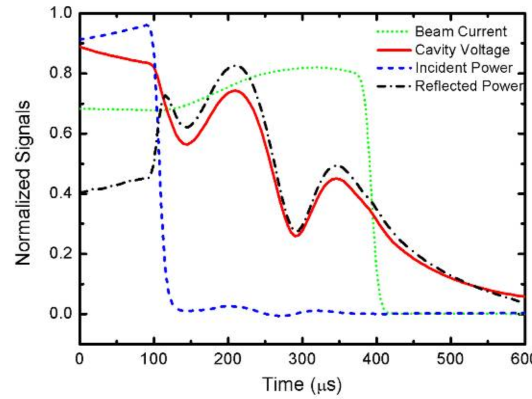

Fig. 9: Beam trip by cavity quench signal

CONCLUSION

The beam current at SSRF has reached 300mA at 3.5GeV, and the DLLRF has successfully maintained the amplitude and phase stability of the cavity field in the SC cavity. SSRF is now operational at 210mA and open for customer use. Some beam trips such as MPS, orbit and etc., may happen during the operation and cut the RF power off. The beam trip diagnostics has successfully distinguished the first fault and is helpful in the improvement of the SRF system.

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