BEAM LOADING EFFECTS IN SSRF STORAGE RING

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Abstract

The beam current in the storage ring of Shanghai Synchrotron Radiation Facility (SSRF) is now normally 240 mA and projected to be raised to 300 mA. Heavy beam loading will be serious and associated Robinson instability needs to be compressed. In this paper, the beam loading effects in SSRF storage ring and methods to increase current limit will be discussed.

INTRODUCTION

The upgrade project of SSRF is under design and the storage ring beam current is aimed to be raised from 240 mA to 300 mA. With the help of long time high power conditioning and the accurate control of low level RF(LLRF) system, long term stability of beam current have been reached with the total RF cavity voltage at 4.8 MV when the current was under 250 mA[1,2]. The beam loading effect has been investigated by many scientists since Robinson first published his work in 1964 [3-5]. It is common to raise the current limit by increasing the total cavity voltage which is inapplicable in SSRF. Ignition happens frequently when the total cavity voltage is raised from 4.8 MV to 5.4 MV. An alternative way is adopting LLRF feedback. By decreasing the resistance seen by beam, direct feedback loop can help improve current limit [6]. The prototype of the feedback loop is based on the digital LLRF (DLLRF) system used in SSRF storage ring.

RF SYSTEM AND BEAM LOADING

Three RF stations supply necessary power for electron beam. Every RF station controlled individually by its own LLRF system have one cavity and one klystron. The general layout of the RF system in SSRF storage ring is shown in Fig. 1.

The interaction between beam and cavity is always simplified as RLC model [4]. The vector relationship of cavity voltage and beam current which is shown in Fig. 2 indicates the equilibrium status where I_b (I_g) represents beam current (power source) component at RF frequency, V_b (V_g) is the voltage induced by I_b (I_g), V_c is the total voltage seen by beam, φ_s is accelerating phase, φ_z is detuning phase and φ_L is beam loading phase.

Fundamental storage ring parameters of RF system were listed in Table 1.

The basic equations of the RF system parameters and vector diagram are:

$$tan\varphi_z = 2Q_e \frac{\Delta\omega}{\omega_{rf}}$$

$$R_L = \frac{1}{2}\frac{r}{Q} \times Q_e$$

$$\vec{V_c} = (\vec{I_b} + \vec{I_g}) \times R_L cos\varphi_z e^{-j\varphi_z}$$

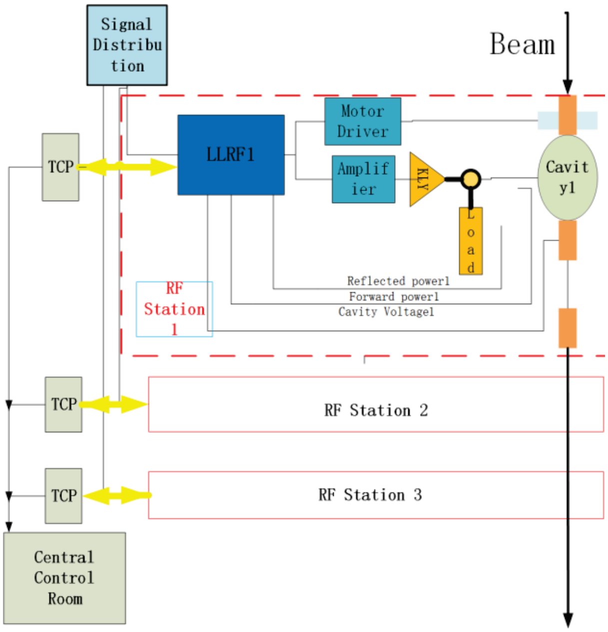

Figure 1: General layout of RF system in the storage ring of SSRF.

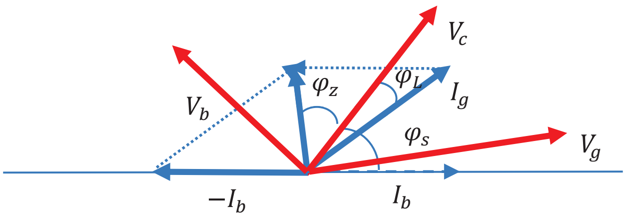

Figure 2: Vector diagram of beam cavity interaction.

It was indicated by Robinson that there will be lack of restoring force for the accelerating phase shift when the beam current is high enough. The critical condition is:

$$\varphi_L + \varphi_Z = \varphi_s$$

Table 1: RF system parameters

Parameter	Symbol	Value
Beam energy	E	3.5 GeV
RF frequency	f_{rf}	499.682 MHz
Beam energy loss (one turn)	ΔE	1.414 MeV
Total accelerating voltage	V_c	4.8 MV
Beam loading phase	φ_L	5~7°
r-over-*Q*	r/Q	90(Ω)
External quality factor	Q_e	1.7×10^5

According to Robinson criterion, beam current limit is determined by:

$$I_{bmax}=\frac{V_c}{\frac{r}{Q}Q_e}\frac{2sin\varphi_s}{sin(2\times(\varphi_s-\varphi_L))}$$

The current limit determined by total cavity voltage is displayed in Fig. 3.

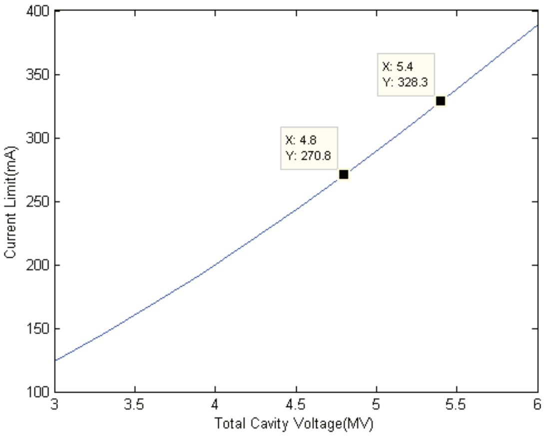

Figure 3: Current limit vs total cavity voltage.

It indicates that the current limit of SSRF is 270 mA. To achieve the goal of 300 mA, total cavity voltage has to be raised from 4.8 MV to 5.4 MV. High power test indicates the superconducting cavity cannot endure such high voltage. Ignition and quench happen frequently when the individual cavity voltage is higher than 1.8 MV.A second way to increase $I_{bmax}$is to decrease the resistance seen by beam by LLRF feedback technology.

LLRF SYSTEM

The LLRF system of SSRF is fully digitalized based on heterodyne structure. The main sketch of the LLRF controller is shown in Fig. 4.

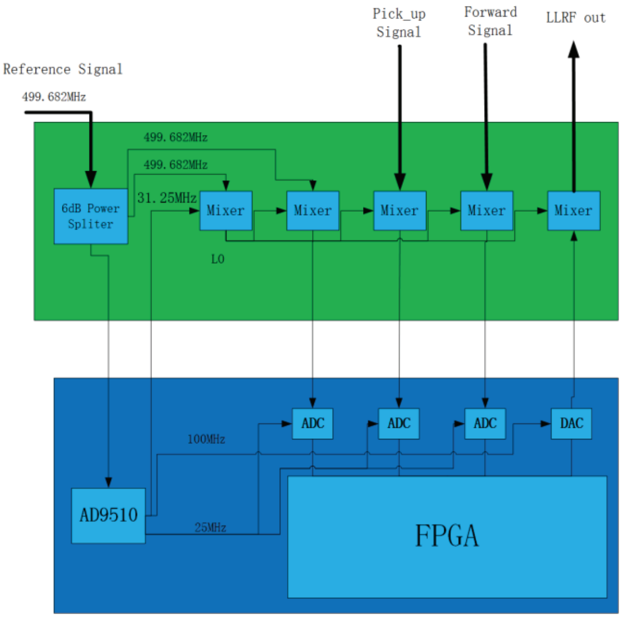

Figure 4: Main sketch of the LLRF controller.

The reference signal is mixed with the 31.25 MHz intermediate frequency (IF) signal which comes from AD9510 and 468.432 MHz local oscillator (LO) signal is then generated. All the signal coming from high level system at 499.682 MHz will be down converted into IF signal and acquired by analog-to-digital convert (ADC) on the digital process board through I/Q technique. The data will be sent into FPGA where the field control and tune control feedback algorithm are executed. The digital output from FPGA will be transformed into analog signal through digital-to-analog convert (DAC) and then up converted into RF signal.

The abstract feedback loop is shown in Fig. 5.With the help of direct feedback loop, resistance seen by beam can be decreased by a factor of (1+*H*),where *H* represents the feedback gain of direct loop. The gain is largely limited by loop delay and total responsive time of the direct feedback loop is 770 μs.The condition to satisfy the goal is:

$$H>0.2$$

It seems insufficient if only direct feedback loop is adopted. D. Boussard has pioneered that beam only requires a low impedance at certain frequencies [6,7]. A comb filter and one turn delay feedback loop can help improve the direct feedback loop gain. It is under design and will be estimated after the test results of direct feedback loop comes out.

CONCLUSION

The beam current at SSRF is now at 240 mA and will be raised to 300 mA. Due to the use of high Q superconducting cavity, beam loading effect will be serious and Robinson instability will limit the maximum current. High power conditioning indicates that the cavity cannot be operated normally because of the frequent ignition. A direct feedback loop based on digital LLRF system, whose gain should be larger than 0.2, is under design to decrease the resistance seen by beam.

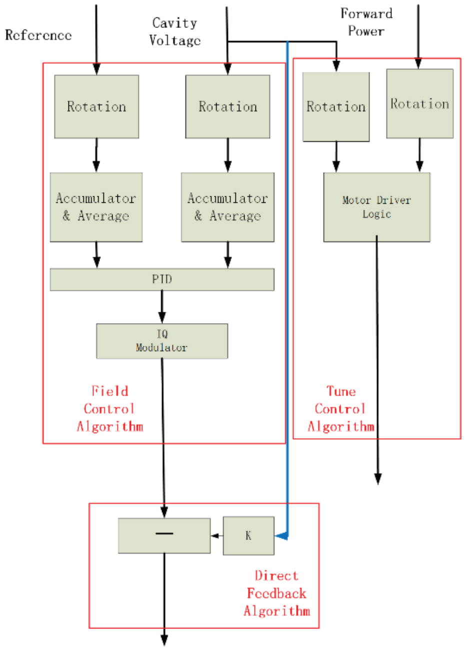

Figure 5: Abstract feedback loop.

REFERENCE

[1] X. Zheng, Y.B. Zhao, H.T. Hou et al, “DLLRF and Beam Trip Analysis in the Storage Ring of SSRF”, in *Proc. of IPAC’10,* Kyoto, Japan, May 2010, paper TUPEA052, pp. 1449-1451

[2] Y. B. Zhao et al, “Development of Digital Low Level Radio Frequency Controller at SSRF”, in *Proc. of IPAC’14*, Dresden, Germany, June 2014, paper WEPME074, pp. 2453-2455

[3] K.W. Robinson, “Stability of Beam in Radiofrequency System”, CEA report CEAL-1010 (1964)

[4] R. Garoby, “Beam loading in RF cavity”, CERN, Geneva, Switzerland, Rep. CERN PS-RF 1211

[5] M.G. Minty, R.H. Siemann, “Heavy beam loading in storage ring radio frequency system”, *Nucl. Instr. Meth.*, 301-308, 1996

[6] F. Pedersen, “RF Cavity Feedback”, CERN, Geneva, Switzerland, Rep. CERN 92-59, 1992

[7] D. Boussard, G. Lambert, “Reduction of the Apparent Impedance of Wide Band Accelerating Cavities by RF Feedback”, *IEEE Trans. Nucl. Sci. Vol. NS-30, No. 4,* 1983