CAVITY-BASED MULTI-PARAMETER BEAM DIAGNOSTICS AT HLS*

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Abstract

Recent developments of the fourth generation light sources needs precious control of beam parameters, such as beam position, transverse emittance, beam density, bunch length, etc.. Non-destructive on-line beam diagnostic methods are then required. As an example, the cavity beam multi-parameter monitor system designed for the HLS photocathode RF electron gun consists of a beam position monitor, a beam quadrupole moment monitor and a beam density and bunch length monitor. The cavity beam position monitor uses a re-entrant position cavity tuned to TM110 mode as position cavity and cut-through waveguides to suppress the monopole signal. Beam quadrupole moment monitor system consists of a square pill-box quadrupole moment cavity, a cylindrical pill-box reference cavity and a waveguide coupling network. TM_{0n0} modes of cavity can be used to work out beam density and bunch length simultaneously. To simplify the design and suppress the whole system here, we use the reference cavity of beam position monitor as beam density and bunch length signal pick-up.

INTRODUCTION

Linac-based X-Ray free electron laser has been the frontier in the research of the fourth generation light source [1]. In order to measure the linac beam emittance, bunch length and other parameters on line, technologies of multi-parameter beam diagnostics based on resonant cavities are proposed and applied at Hefei Light Source high brightness injector. The cavity beam monitor system designed for the HLS photocathode RF electron gun contains three cavity monitors: a position monitor, a quadrupole moment monitor and a beam density & bunch length monitor. The cavity BPM system, which works at 2.448 GHz, consists of a re-entrant position cavity, a reference cavity tuned to TM_{010} mode and a signal processing system. With a noise factor of 10 from the electronics, the theoretical resolution of beam position monitor is 31 nm [2]. The cavity beam quadrupole moment monitor works at 5.712 GHz and consists of two square pill-box cavities used to pick up quadrupole signal, a cylindrical pill-box reference cavity, which can be the same cavity used in cavity BPM system, and a waveguide coupling network. Strength of quadrupole magnets is adjusted to construct a matrix which can be used to work out beam parameters. The reference cavity of position and quadrupole moment monitor also provides TM_{0n0} mode signal [3, 4], which can be used to work out the beam density and bunch length as well [5, 6].

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As pick-up stations for beam diagnostics, resonant cavities can provide signal with large amplitude and high SNR and help to achieve high precision [7]. In this project, method of measuring beam intensity and bunch length simultaneously by a same cavity is first put forward for low repetition and short bunch situation, while a new approach to measure peak current of photocathode RF gun is showed. The TM_{0n0} eigenmodes of cavities are used in combined measurement of bunch length, beam intensity, position and quadrupole moment so that the whole diagnostic system is simplified and compact. More than one eigenmodes of resonant cavities are used in beam intensity measurement in order to get higher precision. High speed data acquisition system based on high speed ADC, high density FPGA and high performance DSP chips is used as signal processing system and the sampling rate can be 1Gsps.

BEAM DIAGNOSTIC SYSTEM OF PHOTOCATHODE RF ELECTRON GUN

Figure 1 shows the sketch of the original beam diagnostic system of the HLS photocathode RF gun. Now this system can be used to calibrate the new cavity-based beam multi-parameter monitor. The system consists of BPMs, FCT, ICT, Faraday cup, flags and multi-slits beam emittance measurement equipment. As shown in Fig. 1, multi-slits method uses screen monitors to intercept the beam and get the emittance. Beam measurement group of NSRL has worked on using stripline BPM to get the quadrupole moment of beam [8]. An s-band re-entrant cavity BPM is also developed [2, 9].

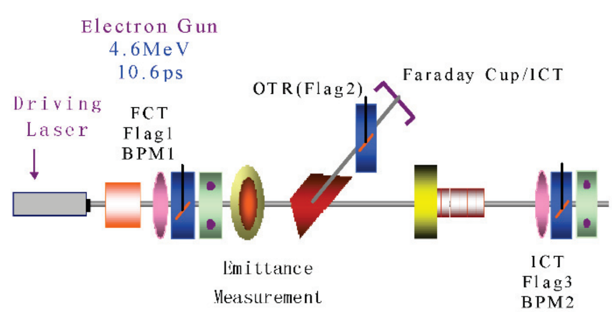

Figure 1: Original beam diagnostic system of RF gun.

On this basis, multi-cell cavity beam monitor is given. The new cavity beam monitor is planned to be installed at the end of the original diagnostic system, showed in Fig 2. NSRL is now upgrading HLS to HLS II, the multi-parameter monitor is designed for the high brightness injector facility, but can also be useful to the HLS II linac.

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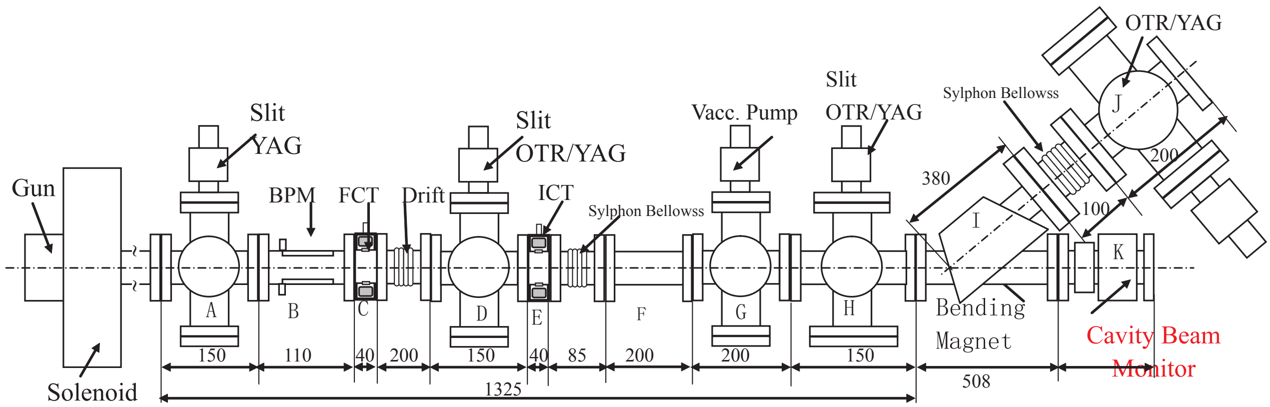

Figure 2: Complex installation drawing of beam diagnostic system.

NON-DESTRUCTIVE BEAM QUADRUPOLE MOMENT MONITOR

Beam emittance is defined by the equation

$$\varepsilon = \sqrt{\sigma_u^2 \sigma_{u'}^2 - \sigma_{uu'}^2} \tag{1}$$

Assume there are two points f and b on beam path, the transformation matrix from f to b is

$\left[M_f^b\right]_x = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}$, $\left[M_f^b\right]_y = \begin{bmatrix} m_{33} & m_{34} \\ m_{43} & m_{44} \end{bmatrix}$, then

there is

$$\sigma_{xb}^2 - \sigma_{yb}^2 = m_{11}^2 \sigma_{xf}^2 + 2m_{11}m_{12}\sigma_{xx'f}^2 + m_{12}^2\sigma_{x'f}^2 \tag{2}$$
$$-m_{33}^2\sigma_{yf}^2 - 2m_{33}m_{34}\sigma_{yy'f}^2 - m_{34}^2\sigma_{y'f}^2$$

In this case, people can change the transformation matrix at least six times and then establish a system of equations and work out σ_{uf}^2, $\sigma_{u'f}^2$ and $\sigma_{uu'f}^2$. [8].

Quadrupole mode of resonant cavities can be used to detect the quadrupole moment of beam [10]. A cavity beam quadrupole moment monitor is then designed.

To get the quadrupole moment of beam, monopole and dipole modes of resonant cavity must be suppressed. Rectangular cavities, especially square cavities, can push the nearest non-quadrupole mode further away and is proved to be a better choice. The power coupled out from the TM220 mode will satisfy,

$$P_{out} \propto \left(x^2 - y^2 + \sigma_x^2 - \sigma_y^2\right)^2 \tag{3}$$

The influence of beam position x and y can be deduced from the dipole moment of beam. Power coupled out from dipole modes of cavity satisfy [2],

$$P_{dipole,x} \propto x, \; P_{dipole,y} \propto y \tag{4}$$

A quadrupole moment monitor was designed. As it is showed in Fig. 5, there will be two quadrupole cavities to couple out skew quadrupole mode and normal quadrupole mode separately. A re-entrant cavity beam position monitor is connected to measure dipole modes.

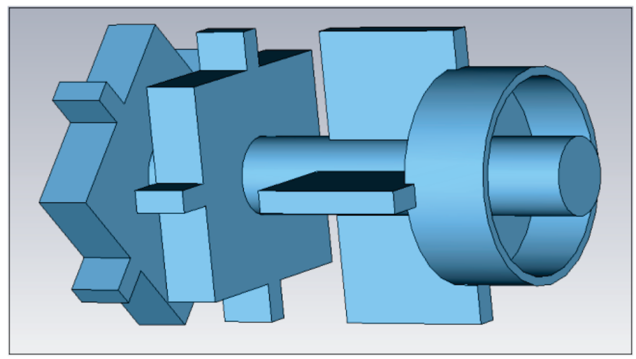

Figure 3: Multi-cell cavity beam monitor.

To pick up signals, network consists of waveguides is used. Waveguide coupling method can suppress the monopole mode leakage in position cavity [2] and both monopole and dipole mode leakage in quadrupole moment cavity. The quadrupole moment monitor works at 5.712 GHz, space to all the non-quadrupole modes is more than 400 MHz. The dipole mode monitor works out beam position at 2.448 GHz.

BEAM DENSITY AND BUNCH LENGTH MONITOR

Method of coupling out the TM_{010} modes of different cavities to work out bunch length are widely used [5, 6], while the reference cavities of cavity beam monitors provides TM_{010} mode signal as phase and beam density reference. It is only natural that the scientists want to use this reference signal to work out the beam density and bunch length as well, the only difficulty is if the beam signal can be coupled out clearly with a high enough amplitude.

For low repetition rate and single bunch photocathode RF electron gun, one can assume that the spectrum of beam is broadband and continuous. Fig. 4 shows the beam spectrum of a 10ps bunch length. Here we can see the spectrum contains abundant components, so it is not necessary to tune the eigenmodes of cavities to high order harmonics. Instead, different TM_{0n0} modes of the reference cavity can be coupled out and afford the beam density and bunch length signal.

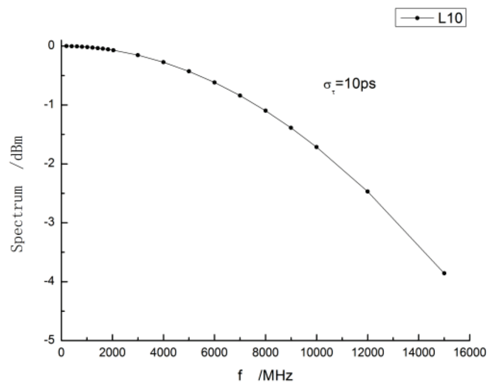

Figure 4: Spectrum of 10ps beam.

For TM_{0n0} mode and TM_{010} mode, there is:

$$\sigma_z = \frac{1}{\omega_0}\sqrt{\frac{Z_n P_1 - Z_1 P_n}{n^2 Z_n P_1}} \quad (5)$$

Where Z is shunt impedance.

To get high SNR, modes with more than 10GHz frequency difference and 3dB amplitude difference are chosen as work modes. In this design, we chose TM_{010} mode and TM_{050} mode. After computer simulation, frequency of TM_{010} mode is tuned to 2448MHz, while resonant frequency of TM_{050} mode is then set to 15193MHz. The beam density and bunch length monitor at HLS works on 2448MHz, which is the same as the cavity beam position monitor, so the reference cavity of the BPM can be used as beam density and bunch length monitor and the whole system is simplified.

HIGH SPEED DATA ACQUISITION SYSTEM

To work out the transverse emittance there should be at least six equations so the parameters in equation (1) can be deduced. Change focusing strength of quadrupole magnet is a proper approach to make up equations that can be solved.

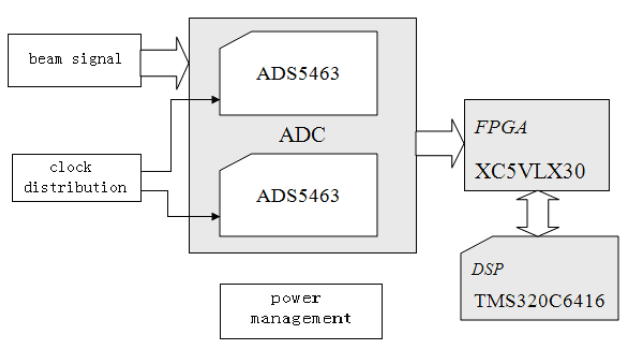

Figure 5: Sketch of high speed data acquisition system for cavity-based multi-parameter beam diagnostics.

Figure 5 shows the sketch of high speed data acquisition system of the multi-parameter beam monitor. The double channel data acquisition system is based on parallel time-interleaved sampling method, using high density FPGA and high performance DSP chips.

As system works at both S-band and C band, down-conversion front-end module is needed. Reference cavity is used to provide amplitude and phase reference signal.

CONCLUSIONS

Multi-cell cavity beam monitor is a way to get transverse emittance, beam position, beam density and bunch length simultaneously. Using cavity beam monitor to replace traditional beam position monitors and beam emittance measurement method is reasonable and feasible. Further work will be meaningful while more computer simulation and cold test is needed.

Work at signal processing system is also useful because non-destructive diagnostic method needs high speed signal processing module with good accuracy.

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