DESIGN OF CAVITY BEAM MONITOR AT HLS *

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Abstract

X-FEL requires precious control of beam position and transverse emittance. Non-destructive on-line beam diagnostic methods are required. The cavity beam monitor system designed for the HLS photocathode RF electron gun consists of a cavity beam position monitor and a beam quadrupole moment monitor system. 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. Cold test results showed that position resolution of prototype BPM is better than 3 µm. Beam quadrupole moment monitor system consists of a square pill-box quadrupole moment cavity, a cylindrical pill-box reference cavity, a waveguide coupling network and a superheterodyne receiver used as front-end signal processing system. The whole system works at 5.712 GHz. Strength of quadrupole magnets is adjust to construct a matrix which can be used to work out beam parameters.

INTRODUCTION

X-FEL based on linac is one of the most attractive topics in accelerator science and related areas nowadays. It requires electron beam with high brightness and high stability, thus precious control of beam transverse emittance is essential. Non-destructive beam emittance measurement methods usually base on getting the quadrupole moment of a beam non-destructively [1-7]. Hefei light source is to complete an upgrade in two years. In this upgrade plan a high brightness injector based on photocathode RF electron gun, which can also be used to study FEL, is installed. The beam from photocathode RF gun has a quality of 1nC and energy of 4~5 MeV and the normalized emittance should be no more than 6mm·mrad. Position resolution of the beam position monitor (BPM) for the new injector should be better than 10 µm.

For a substantial improvement in position resolution of BPM system, HLS decided to use cavity BPM, which promises much higher position resolution than the stripline BPM used at HLS before [8]. It is logical that eigenmodes of resonant cavities can be used to pick up quadrupole moment information of electron beam non-destructively and accurately.

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The cavity beam monitor system designed for the HLS photocathode RF electron gun contains two cavity monitors: a cavity beam position monitor and a beam quadrupole moment monitor. The cavity BPM system, which works at 2.448 GHz, consists of a re-entrant position cavity, a reference cavity tuned to TM010 mode and a signal processing system. With a noise factor of 10 from the electronics, the theoretical resolution is 31 nm [9]. Prototype of the s-band cavity BPM is manufactured and cold test is then performed. The position resolution of cavity BPM system on-line can be better than 3µm. 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, a waveguide coupling and a superheterodyne receiver used as front-end signal processing system. Strength of quadrupole magnets is adjusted to construct a matrix which can be used to work out beam parameters.

BEAM DIAGNOSTIC SYSTEM OF PHOTOCATHODE RF ELECTRON GUN

The photocathode RF gun is now trial running after aging stage completed. The energy of bunch is now limited to about 2 MeV. The emittance measurement method used is multi-slits method.

Figure 1 shows the sketch of original beam diagnostic system designed for the photocathode RF gun. The system consists of BPMs, FCT, ICT, Faraday cup, flags and multi-slits beam emittance measurement equipment. As shown in Figure 1, multi-slits method uses screen monitors to intercept the beam and get the emittance.

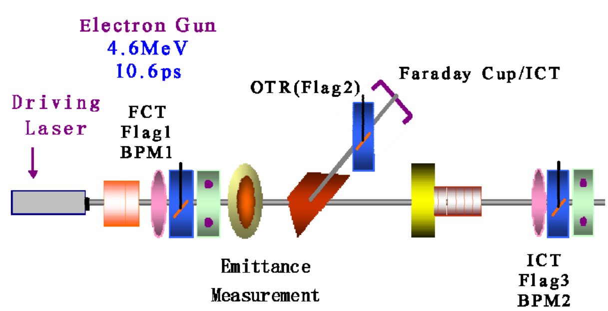

Figure 1: Original beam diagnostic system of RF gun

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 [9, 10]. On this basis, multi-cell cavity beam monitor is given. The new cavity beam monitor will be installed at the end of the original diagnostic system, showed in figure 2.

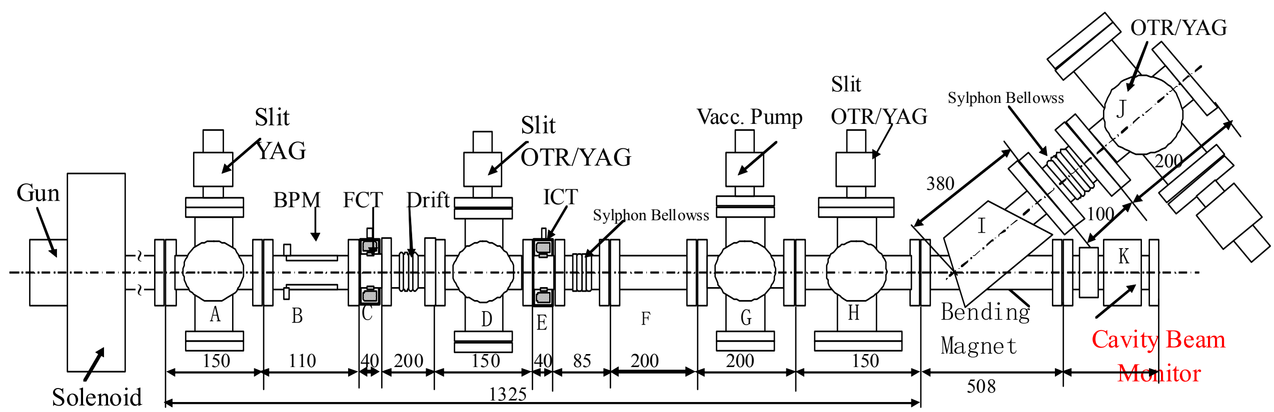

Figure 2: Complex installation drawing of beam diagnostic system

RE-ENTRANT CAVITY BPM

Re-entrant cavity has much smaller size and much lower Q factor than a pill-box cavity with same resonant frequency of TM110 mode. Size of the system can be controlled and proper waveguide be chosen easily. It can still supply large position signal though abeam loses less energy in the re-entrant cavity [9.10].

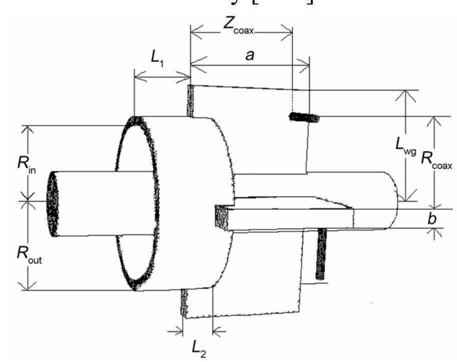

Figure 3: Structure of vacuum part of BPM.

Figure 3 shows only vacuum part of pick-up station since the thickness of metal walls is optional. Cold test platform of re-entrant cavity BPM is showed in Figure 4.

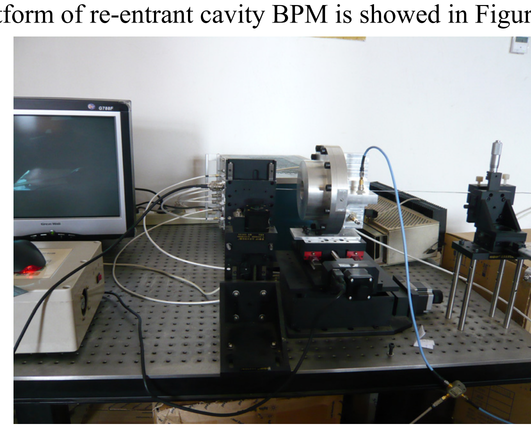

Figure 4: Sketch of the calibration platform.

The real resolution can be estimated as

$$\begin{cases} \delta_x = 1.91\mu\text{m} \\ \delta_y = 2.05\mu\text{m} \end{cases}$$

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

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

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 [6]. 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 [9],

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

A quadrupole moment monitor was designed. As it is showed in figure 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.

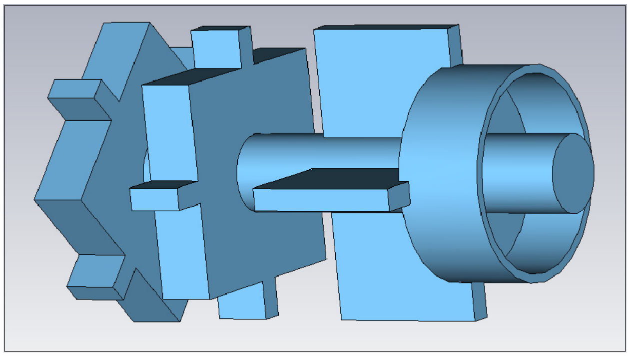

Figure 5: Multi-cell cavity beam monitor

To pick up signals, network consists of waveguides is used. Waveguide coupling method can suppress the monopole mode leakage in position cavity [9] 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.

SIGNAL PROCESS OF CAVITY BEAM MONITOR

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 6 shows signal processing system of beam quadrupole moment monitor. As system works at C band, down-conversion front-end module is needed. Reference cavity is used to provide amplitude and phase reference signal.

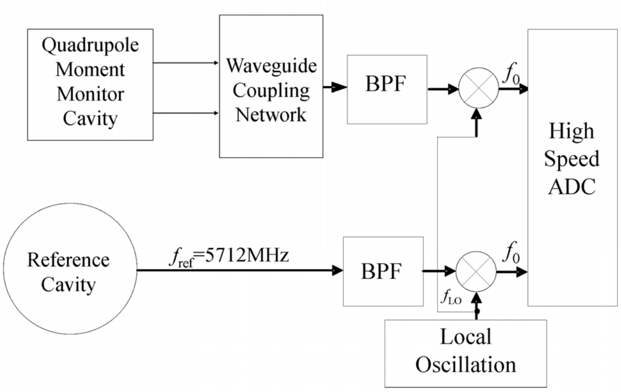

Figure 6: Signal processing system of beam quadrupole moment monitor

Libera digital processors developed by Instrumentation Technologies, d.o.o provide a useful signal processing method that can process signal at 204MHz. Use libera as high speed ADC and signal processing module can simplify the design of front-end module.

CONCLUSIONS

Multi-cell cavity beam monitor is a way to get beam emittance and position 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.

REFERENCES

[1] N. Barov, J.S. Kim, et al. High-Precision Resonant Cavity Beam Position, Emittance and Third-moment Monitors. Proceedings of PAC 2005, p4311-4313

[2] S.J. Russell. Emittance Measurements of the Sub-Picosecond Accelerator Electron Beam Using Beam Position Monitors. Rev. of Sci. Instrum. 70 (2), 1999

[3] Jansson, D.J. Williams. A New Optimised Quadrupole Pick-Up Design Using Magnetic Coupling. Nuclear Instruments and Methods in Physics Research A 479, p233 – 242, 2002

[4] Jansson. Noninvasive Single-Bunch Matching and Emittance Monitor. Phys.Rev.ST Accel.Beams 5:072803, 2002.

[5] J.S. Kim, R. H. Miller, et al. Design of a Standing-Wave Multicell Radio Frequency Cavity Beam Monitor for Simultaneous Position And Emittance Measurement. Rev. Sci. Instrum. 76, 073302 , 2005

[6] J.S. Kim, C.D. Nantista, et al. Resonant-cavity Approach to Noninvasive, Pulse-To-Pulse Emittance Measurement. Rev. Sci. Instrum. 76, 125109 , 2005

[7] M.C. Ross, Laser-Based Profile Monitor for Electron Beams. Proceedings of PAC 2003, p503-507

[8] P. Li, B.G. Sun, et al. New Methods of Measuring Emittance Using Beam Position Monitors. Proceedings of 2007 IEEE Nuclear Science Symposium Conference, p1675-1678

[9] Q. Luo, B.G. Sun, et al, "Design of s-band re-entrant cavity BPM", Nuclear Science and Techniques, 2009, 20(03): 133-139

[10] Q. Luo, B.G. Sun, et al, "Beam Position Monitor with Racetrack Cavity", High Power Laser and Particle beams, 2010, 22(7): 1635-1639