DEVELOPMENT OF A HIGH RESOLUTION BEAM POSITION MONITOR FOR NSRRC VUV/THz FEL

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Abstract

Beam position monitors (BPM) have been widely used on linear colliders and free electron lasers for beam-based alignment and feedback systems. A laser driven photo-injector system has been constructed in NSRRC. This injector has the capability to deliver short relativistic electron beam at high peak current for novel light source R&D. A 2.5 GHz, BPM that can be used for high precision beam position measurement has been designed. The BPM were modified to separate frequency between the horizontal and vertical dipole signals, as well as a reduction of the monopole signal. The design has been simulated by CST. A prototype has been built for verification of theoretical predictions. Microwave bench measurement has been made to compare with the computer simulation results. The progress of our work will be presented in this paper.

INTRODUCTION

The VUV/THz FEL system in National Synchrotron Radiation Research Center is shown in Figure 1.Electron beam generated from this system can achieve femtosecond level. For old beam position monitor system-button BPM, it's too short to detect it. So in this paper we design a 2.5 GHz cavity BPM based on the VUV/THz project proposed by NSRRC. This article first start from the structure and physics research of the BPM, calculate the desired BPM form and resolution length. And then use HFSS Eigen-mode solver to simulate microwave characteristics and adjust the size of cavity so that cavity have the same frequency and working in the right mode. Furthermore, we simulate the variable of BPM when the electron beam pass through cavity by using CST Particle Studio Wakefield solver. It can achieve 2.2μm of resolution based on our design.Finally,we manufacture a prototype to compare the result between simulation and measurement.

PRINCIPLE OF CAVITY BPM

The cavity BPM is a cylindrical cavity likes pillbox. When electron beam pass through the cavity, it will excite many EM mode in cavity. But for the application as BPM the lowest transverse magnetic dipole mode TM110 is of interest. Because it's longitudinal field component couples to the beam with an almost linear dependence to the beam displacement r.

$$E_z = CJ_1\left(\frac{j_{11}r}{R}\right)e^{i\omega t}\cos\varphi \qquad (1)$$

where C is a constant that represents the field amplitude,J_1 is a first order Bessel function of the first kind,$j_{11} \cong 3.832$ is the first root of $J_1(r) = 0$,R is the cavity radius.

When the EM mode was excited, we can obtain the signal out of the cavity. The voltage amplitude of output signal from TM110 cavity can be written as[1]

$$V_{RF} = A_1qy + jA_2qy' + jA_3q + V_N \qquad (2)$$

where q, y and y' are the beam charge, the beam position and the slope of the beam trajectory.A_1qy is beam position signal which is the in-phase component of TM110 mode.jA_2qy' is beam angle signal which is 90 degree out-of-phase from the beam current. It can provide an useful information of dy/dz.jA_3q is common mode leakage of TM010 mode through the band-pass filter.V_N is thermal noise in the detector circuit. To obtain clearly beam position from this equation. We still need the information of beam charge and phase reference. Therefore, another cavity TM010 mode cavity is prepare to provide charge and phase information.

The output signal we obtain from antenna are combined in a hybrid or a Magic-T, the TM110 signal appears at the Δ-port. It can help us to reject the common mode signal in third term of equation. Then pass through the band-pass filter to filter higher and lower frequency signal, mix with reference signal from TM010 mode cavity in synchronous detector. Finally, use digitizer change digital signal to analog signal.

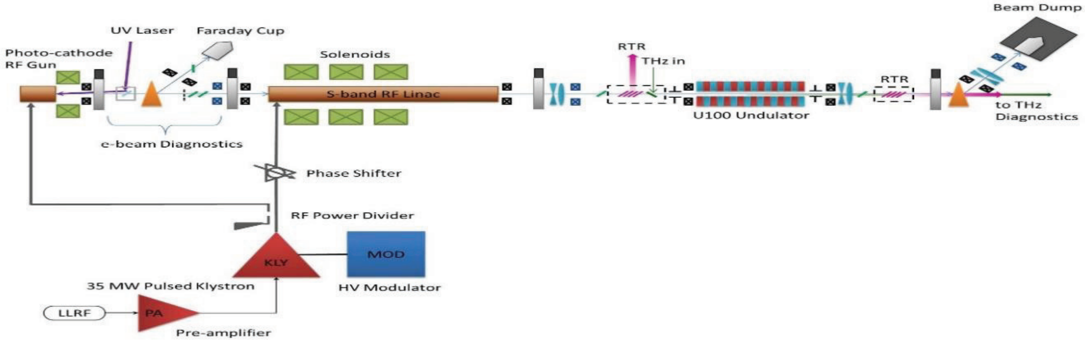

Figure 1: Layout of VUV/THz FEL system in NSRRC.

DESIGN OF S-BAND CAVITY BPM [2,3]

When an electron bunch passes through a cavity, the eigenmodes of the EM field are excited in cavity. In the linear range, the TM110 mode intensity is proportional to the beam offset. However, when electron bunch passes near the center of the cavity, the amplitude is very small. Therefore, it's needed to carefully design BPM so that we can obtain the best signal out of cavity.

Cavity Radius and Length

In our NSRRC VUV/THz system, we need to design a 2.5 GHz beam position monitor. The TM mode frequency of a cylindrical cavity is

$$f_{kmn} = \frac{c}{2\pi}\sqrt{\left(\frac{j_{km}}{r}\right)^2 + \left(\frac{n\pi}{L}\right)^2}, \quad (3)$$

where r is the cavity radius, L is the cavity length, and j_{km} is the mth zero of the kth Bessel function. Based on this formula, we can directly estimated the radius of the cavity for the dipole mode frequency to be 2.5 GHz, because the resonant frequency of dipole mode are not dependent on the cavity length.

When we design the cavity length, the energy of excited dipole mode and mode separation should be considered. In our case, because of our small beam charge and low frequency, we want to increase the cavity length so that the (R/Q) and beam position signal for cavity can enhance. Finally, the decided cavity radius and length as Table 1 with computer simulation code HFSS.

Table 1:Design Considerations

	TM110 cavity	TM010 cavity
Frequency (GHz)	2490	2495
Radius (mm)	72	49
Length (mm)	20	20

Coupling Slot

In coupling slot designed, we have two considerations. First is slot width, the width of the coupling slots in the two planes in design is different. [2] This design can achieves some frequency separation between the horizontal and vertical polarisations of the dipole mode which allow to improve the rejection of the cross coupled signal once the signal is digitised. The result of this design is shown in Figure 2. We can see that achieve 5MHz frequency separation. In our case, our quality factor is 2475 so that the bandwidth of cavity is smaller than 5MHz, it's enough that the cross-coupled signals fall outside and so are suppressed.

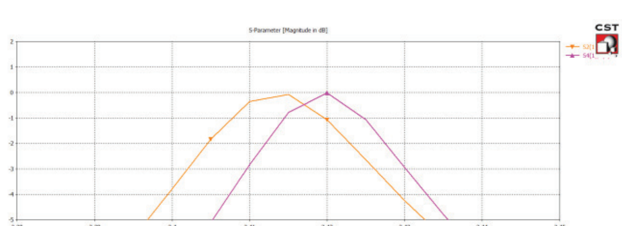

Figure 2 : S-parameter response of the dipole mode.

Second is slot length, if each electron bunch has Gaussian distribution, the excited voltage at the cavity gap is given by[3]

$$V_{out} = \frac{\omega q}{2}\sqrt{\frac{Z}{Q_{ext}}\frac{R}{Q}}\, exp\left(\frac{-\omega^2\sigma_z^2}{2c^2}\right), \quad (4)$$

where Z is the gap impedance, q is the beam bunch charge, σ_z is the beam bunch length in the longitudinal direction. R/Q is a function of the beam offset and Q_{ext} is determined from the coupling between the cavity and the waveguide. Therefore, the output voltage is dependent on the beam offset and the size of slot. Generally, the coupling slots are positioned where the flux of magnetic field is the strongest to make the transmittance to the waveguides maximized. In our case, the position is 59 mm from the center. We scan with CST code at this point shown in Figure 3. We can see that position signal is decrease in line with expectations. Finally, the dimensions of slot were 45mm × 8mm(6mm).

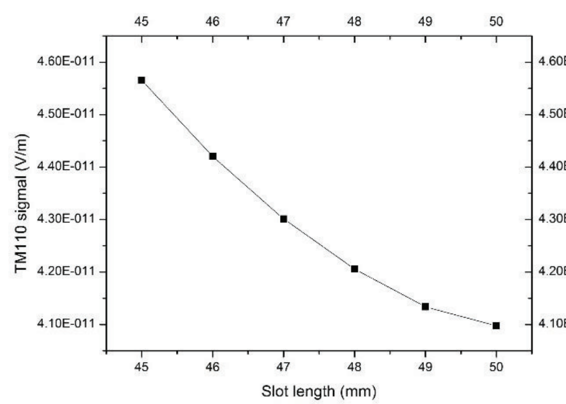

Figure 3: Position signal decrease when slot length increase.

Wavequide

In deciding the wavequide dimensions we have two considerations. First is the cutoff frequency of wavequide. Even though the cavity is designed the dipole mode frequency to be resonant to the electron bunches, the noise from monopole mode of which frequency is 1.59 GHz is not ignorant. Therefore, we design the cutoff frequency of waveguide is 2 GHz that higher than the monopole mode frequency. So the dipole mode is coupled to the TE10 mode of the wavequide and monopole mode is suppressed. Then, we use simulation code CST to check the design, the results are shown in Figure 4.

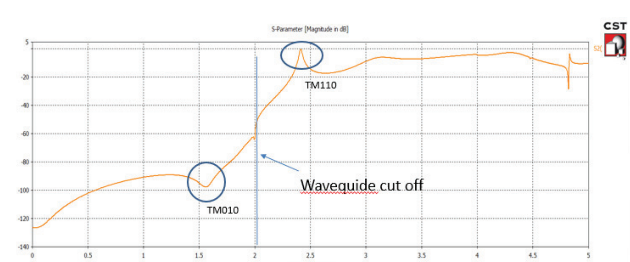

Figure 4 : S-parameter response of BPM.

ISBN 978-3-95450-147-2

Second is the wavequide length. In deciding wavequide length, we should notice that the lowest resonant frequency (TE110) is higher than the dipole frequency. Because the wavequide can act like a cavity due to the reflection of dipole mode, if the coupling between antenna and wavequide is not critical. Finally, the dimension of our case is 75 mm × 14 mm × 85 mm.

Full Structure Simulation

After deciding all parameters of cavity, we use CST Particle stuio-Wakefield solver to estimate the output signal from cavity. The 3D structure is shown in Figure 5 and Figure 6 is FFT of the port signals.

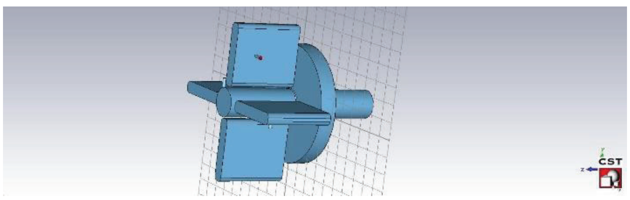

Figure 5 : 3D structure of cavity BPM.

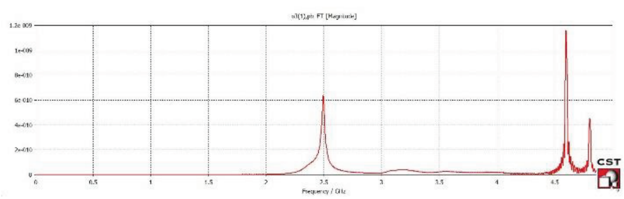

Figure 6 : FFT of the port signals.

Prototype

For the 2.5 GHz BPM prototype have been fabricated, with the aim to both validate the simulation results. The pickup body both the position and reference cavities made of stainless steel. We use Soildwork to design it.

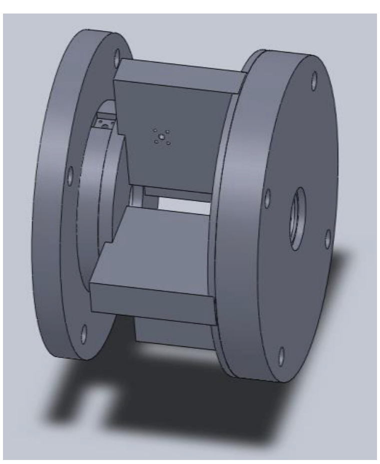

Figure 7 : Prototype of our cavity.

CONCLUSION

A 2.5 GHz BPM for NSRRC VUV/THz FEL has been designed and the prototype is currently in production. Next, we will measure microwave bench for prototype compare to simulate. In table 2, shown the simulation results. The resolution is achieve 2.2 μm which is in line with expectation.

Table 2 : Parameters of TM_{110} Cavity BPM

Frequency (GHz)	2.49
Cavity radius (mm)	70
Cavity length (mm)	20
Quality factor	2475
Resolution (μm)	2.2

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ISBN 978-3-95450-147-2