DESIGN OF A SUBMICRON RESOLUTION CAVITY BPM FOR THE ILC MAIN LINAC

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Abstract

A 500 GeV center-of-mass International Linear Collider (ILC), currently under R&D development, is foreseen as next generation High-Energy Physics (HEP) instrument. High resolution Beam Position Monitors (BPMs) are necessary for preservation of the low emittance beam, i.e. to steer the beam along an optimal trajectory through the Main Linacs of the ILC. We present the cavity BPM developed at Fermilab within ILC collaboration. This monitor will be operated at cryogenic temperature and rigidly attached to the quad magnet. The same cylindrical cavity is used to obtain the signals from both dipole and monopole modes excited by beam. Such a scheme makes the BPM more compact for placing it inside the magnet space and simplifying the signal processing. The ceramic windows are brazed inside coupling slots for vacuum isolation and easy cavity cleaning. In order to measure a single bunch trajectory within 300 ns timescale we use resonant coupling to lower cavity Q-factor. We will present a BPM detailed numerical study and analyze its tolerance requirements for submicron resolution.

INTRODUCTION

The proposed International Linear Collider [1] requires a very precise control of the beam parameters by using high resolution beam instruments. Simulations quantify the need of BPMs with < 1 μm resolution in the Main Linacs and other areas of the ILC, to preserve the low vertical beam emittance by correction of non-linear field effects. A cold L-Band cavity BPM is being developed at Fermilab in order to meet these requirements. The design is based on TM_{110} dipole selective mode coupling [2,3]. Since BPM will be installed to the superconductive quad magnet we are limited in available space and have to follow certain cryogenic technology rules such as material ultra-cleaning. Therefore we implemented two novel features to BPM design. The first one is utilization of four vacuum tight coupling slots with brazed ceramic windows and the second one is the conception of one common cavity as both monopole and dipole signal source. The ceramic windows separate closed waveguides from the main BPM cavity and relax the problem of ultra cleaning while using a common cavity allows to save double longitudinal space. In this paper we also propose the symmetrical signal processing scheme. The main idea is to tune monopole and dipole modes frequencies in such a way as to make the reference frequency exactly in middle between them. This ensured that the down-converter electronics for dipole and monopole mode signals can be made almost identical. Finally we will present the detail numerical analysis of mechanical tolerance requirements to reach submicron resolution using such a cavity BPM.

CAVITY BPM DESIGN

The proposed microwave BPM consists of the simple circular cavity exited in the TM_{110} mode by an off-axis beam. General view of BPM model is shown in Fig. 1.

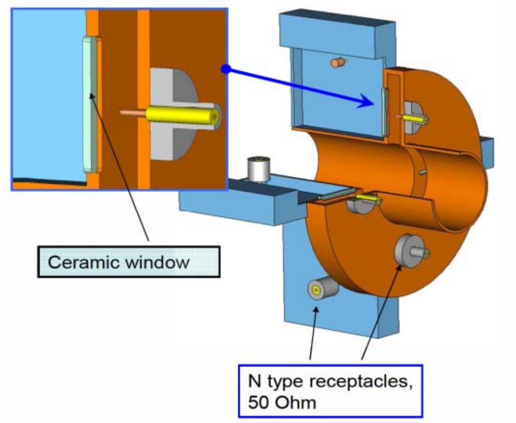

Figure 1: FNAL L-Band Cavity BPM.

The cavity is loaded with coupling ports. Four ceramic windows utilize magnetic coupling with dipole modes and extract beam position signals in two orthogonal planes. Another four N-type coaxial vacuum feedthrough are connected to two hybrids in pairs and provide monopole signal to measure a bunch charge.

Table 1. Main BPM Parameters

Monopole mode frequency , *f010* GHz	1.120
Dipole mode frequency, *f110* GHz	1.470
Loaded *Q* (both monopole and dipole)	~500
Beam pipe radius, mm	39
Cavity Radius, mm	113
Cavity Length, mm	15
Waveguide, mm	120x25
Ceramic window (Al_2O_3, $\varepsilon=9.4$), mm	50x5x3
Dipole mode sensitivity, V/nQ/mm	0.24
Monopole mode sensitivity, V/nQ	6
BPM resolution, μm	<1
BPM dynamic range, mm	±1

The copper material was chosen for cavity production to minimize possible cryolosses. Ceramic window is brazed in a special designed nonrigid ring slot with narrow walls to compensate ceramic temperature

*This work was supported by Fermi National Accelerator Laboratory, operated by Fermi Research Alliance, LLC under contract No. DE-AC02-07CH11359 with the United States Department of Energy.

deformations due to a different expansion coefficient compare to the copper. The main design parameters of BPM are given in the Table 1.

In order to increase dipole mode coupling while keeping the same sizes of ceramic window we approached the idea of resonant coupling. The waveguide to coaxial transition forms itself low-Q resonator with resonance frequency close to the dipole mode. It helps to increase the overall coupling coefficient by factor of 10. The result of HFSS simulation is shown in Fig. 2.

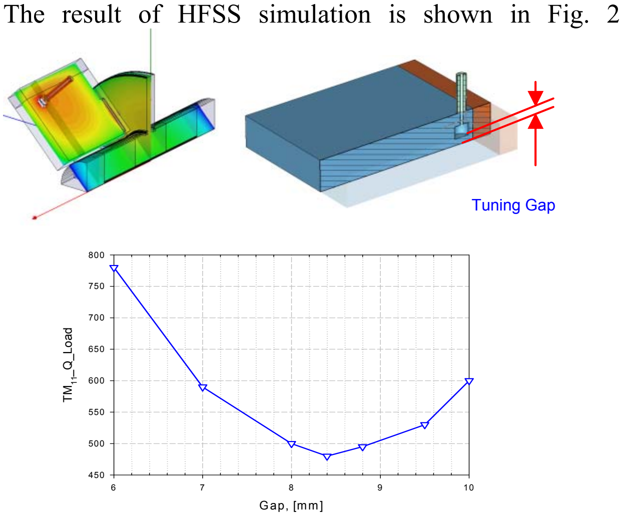

Figure 2: Tuning of resonant dipole mode coupling to coaxial pickup.

The short end of the waveguide is filled with alumina ceramic material as well. This solution gives us more radial space to fit BPM inside cryomodule.

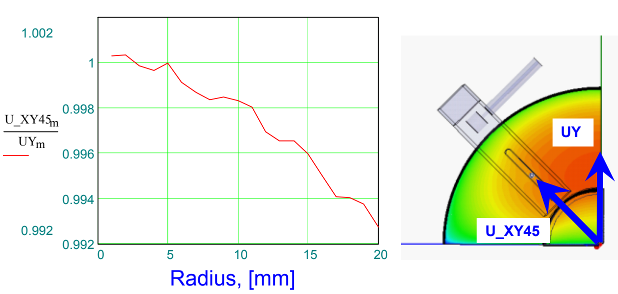

Figure 3: Dipole mode distortion by coupling slots vs radius.

The coupling slots perturb the theoretical field distribution. That breaks the dipole mode cosine azimuth dependence and causes the pseudo-quadrupole components occurrence. We compare two signals rotated to π/4 in respect to each other. The result is illustrated in Fig. 3. The error is less than 10^{-3} up to 5mm of a beam offset.

PROCESSING OF SYMMETRIC CAVITY BPM SIGNALS

The major part of the processing of the dipole (TM_{110}) and monopole (TM_{010}) mode signals of the cavity BPM will handled in the digital domain. An ATCA-standard based digitizer board, utilizing 16x 500 MS/s ADCs (12-bit) and 16x 1200 MS/s DACs (14-bit), is currently under development. It processes the analog signals from DC to 200 MHz, and extends the frequency range to > 1GHz by applying undersampling techniques.

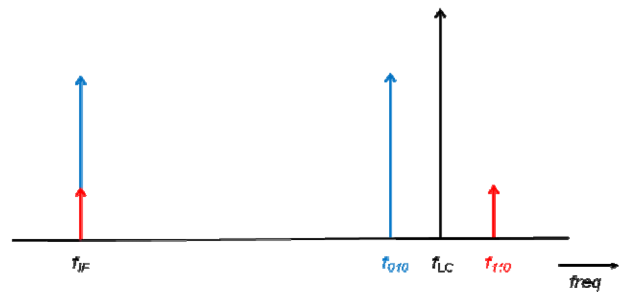

Fig. 4: Symmetric down-conversion of dipole and monopole-mode signals.

Some minimum signal processing however has to be still accomplished in the analog domain. The effective digitizer resolution is mainly limited by clock jitter, so a digital direct down-conversion (DDC) of the cavity signals is not applicable. Therefore analog down-mixing of the dipole (f_{110}) and monopole (f_{010}) mode to an intermediate frequency (f_{IF}) is required. The signal processing is simplified by designing the cavity dimensions such that $f_{IF} = f_{110} - f_{LO} = f_{LO} - f_{010}$

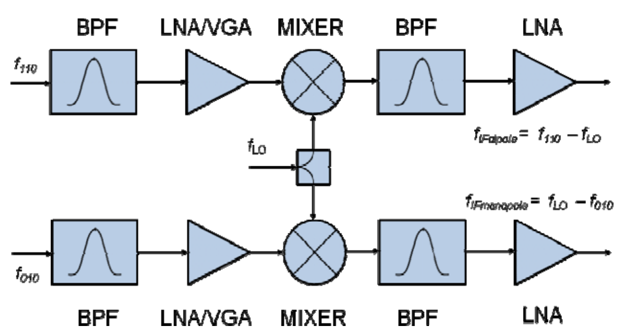

Fig. 5: Analog downconversion of symmetric dipole- and monopole mode signals.

The local oscillator reference frequency f_{LO} is located arithmetically between dipole and monopole mode frequencies (see Fig. 4). Now the down-converter electronics for dipole- and monopole mode signals can be made almost identical (Fig. 5), except a lower gain is required for the monopole mode signal. The LO signal, as well as the ADC clock are derived and locked to the accelerator f_{RF}. The IF signals are digitally down-converted to baseband, both for their inphase (I) and quadrature (Q) components. In further stages the magnitude and phase are computed to normalize the dipole mode signal to the bunch intensity (monopole mode signal), which gives the wanted beam position. The computed phase of the dipole mode signal provides the sign information for the beam displacement data.

TOLERANCE

Fabrication errors may cause the significant degradation of BPM measurement accuracy. Important reasons are resonant frequencies shift, monopole mode leakage to the pickup port and orthogonality violation between two polarizations of dipole mode. The cavity frequencies shift has an influence on further signal processing because we are locked to accelerator RF frequency as the reference. The monopole mode coupling results the blind spot near BPM electrical center and therefore limits BPM resolution. The dipole modes nonorthogonality induce cross coupling between *x-y* pickup ports. While the symmetrical loaded *x-y* coupling can be removed numerically, the general unpredictable reflections from electronics and feedthroughs may also deteriorate the BPM dynamic range.

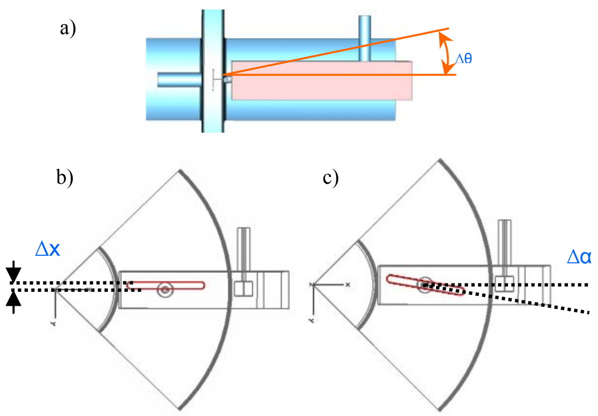

Figure 6: Three cases of slot misalignments: a) tilt, b) shift, c) rotation.

We take into account three possible misalignments as shown in Fig. 6 and calculate their influence on BPM resolution.

Frequency Tuning

The calculated central frequency *(f110+f010)/2* sensitivity versus cavity radius is about 0.011 MHz/μm. We believe that mechanical tolerances 10 μm together with low cavity loaded Q-factor allows us to eliminate the additional frequency tuning tools and simplify final BPM construction.

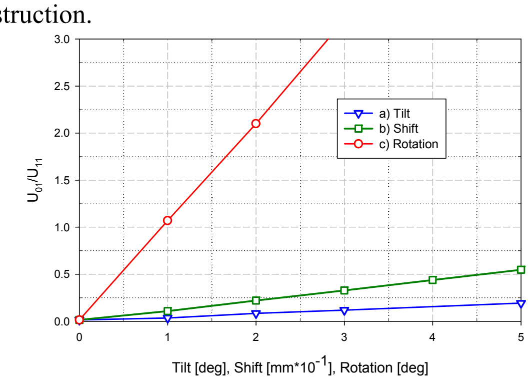

Figure 7: Monopole mode output signals normalized to dipole signal at 1 μm beam offset.

Monopole to Dipole Mode Coupling

Misalignments result in non-zero projections of the magnetic or electric field components of the TE_{10} mode in the coupling slot, produces monopole mode coupling to the waveguide. For the comparison we normalized the output monopole signal to the dipole one at 1 μm beam offset taking into account electronics passband and frequency discrimination. The results are summarized in Fig.7. The monopole mode coupling is most sensitive to the slot rotation misalignment which has to be bellow 1 degree to get the submicron BPM resolution.

Dipole Modes Orthogonality

Waveguide to coaxial transition brakes coupling symmetry and hence the dipole modes orthogonality. The slot misalignments particularly enhance this effect. We calculated the *x-y* ports cross coupling for the cases b) and c) (see Fig.6) and presented results in Fig.8 and 9.

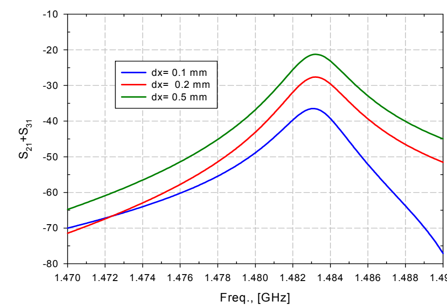

Figure 8: Dipole modes *x-y* cross coupling, case b).

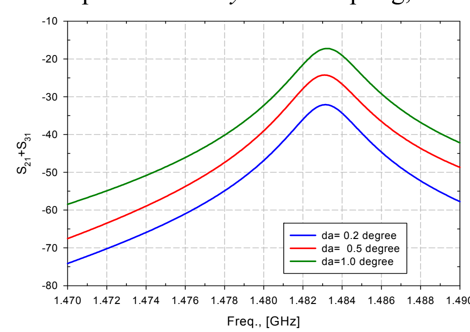

Figure 9: Dipole modes *x-y* cross coupling, case c)

Assuming possible signal reflections from the electronics of order of -30 dB one can choose maximum *x-y* cross coupling bellow -30 dB to get the ±1 mm total BPM dynamic range with submicron resolution.

CONCLUSION

We designed the prototype of cold cavity BPM for ILC project. New approaches such as the common dipole-monopole cavity and ceramic vacuum windows allow us to meet the ILC BPM requirements. Submicron resolution can be achieved with acceptable mechanical tolerances.

REFERENCES

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