BEAM POSITION MONITOR FOR THE TESLA ENERGY SPECTROMETER

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Abstract

An energy spectrometer is to be installed at the beam delivery system of the TESLA linac. It should have an energy resolution of a few 10^{-4} around 450GeV. This demands a very high precision beam position measurement – less than 1µm. A cavity beam position monitor is proposed, because of its high sensitivity. The cavity is a pillbox with a slot, slicing it, which ends in output waveguides. This leads to a strong dipole mode (TM110) coupling, which depends on the beam offset and a very weak coupling to the common mode (TM010), which is independent of the offset, but much stronger excited. Thus, the common mode is heavily suppressed and the beam offset can be measured with a very high resolution.

The paper gives the detailed design of the slotted cavity BPM.

1 INTRODUCTION

The energy of the TESLA (TeV Energy Superconducting Linear Collider) beam should be measured extremely precise to provide good tolerances of high-energy physics experiments. A magnetic spectrometer is proposed to realize the energy measurement (Fig.1) [1]. The beam is deflected from its original direction by a magnet. The Beam Position Monitors (BPMs, blue circles on Fig.1) measure this deflection. The resolution of the spectrometer is [1]:

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{\Delta\int Bdl}{\int Bdl}\right)^2 + \left(\frac{\Delta\theta}{\theta}\right)^2 \qquad (1)$$

The needed resolution of the spectrometer is a few 10^{-4} [1]. The magnetic field can be mapped with a resolution of $3*10^{-5}$. With 100µm magnets alignment we get that the required spatial resolution of BPMs is less than 1µm (for the scheme on Fig.1). It is proposed to use a slotted cavity BPM.

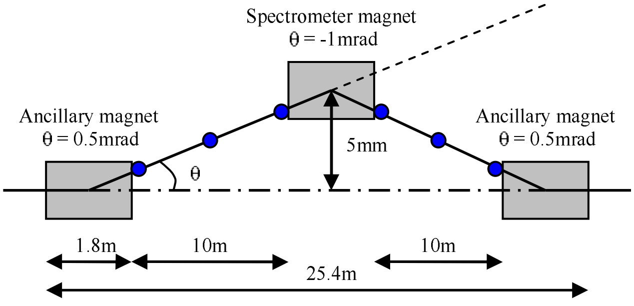

Figure 1: The foreseen spectrometer scheme.

The idea to use a slotted cavity for the beam position measurement is not quite new [2]. A pillbox cavity with rectangular slots slicing the cavity is used (Fig.2).

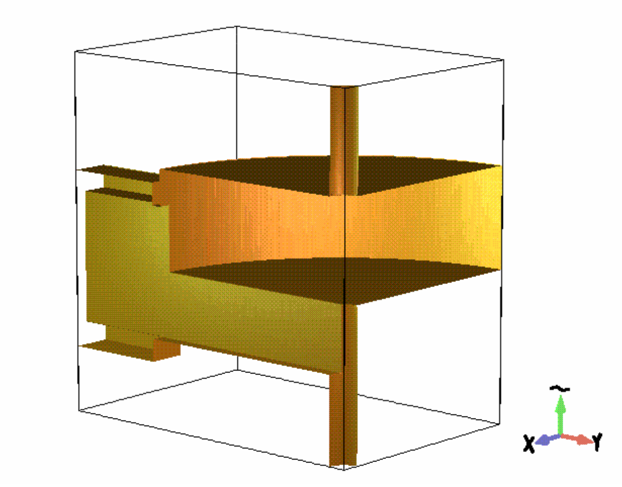

Figure 2: Cavity BPM with damping slots.

A bunch, travelling along the cavity axis with some offset from its centre, excites in particular monopole modes, like TM010, TM020, dipole modes, like TM110, quadruple modes etc. The strongest of them is the common mode, TM010 (Fig.3), it has high R/Q. As other monopole modes, it is independent of small beam offset and depends on bunch charge. The mode of interest is the dipole mode, TM110 (Fig.4), because it depends on both – bunch charge and offset. The TM110 can be coupled out from the cavity using antennae [3]. At the same time, other modes are also coupled, in particular the common mode. This helps, when the measurement is not very precise, because the common mode signal can be separated in the electronics and used for charge measurement. Unfortunately, this does not work for the precision of 1µm, because the isolation between charge and offset channels is relatively low. This means that another type of dipole mode selection should be applied, and this is done by using of slot and output waveguides.

The common mode couples to the TE11-wave in the waveguide, while the dipole mode couples to the TE10-wave (Fig.5). However, the waveguide is designed in the way that the TE11-wave is well below cut-off at the common mode frequency. In that way the dipole mode is selected and the common mode is rejected strongly. (The similar technology is used for HOM damping in CLIC structure and in KEK). Strong common mode rejection means low background signal level and, consequently, high resolution.

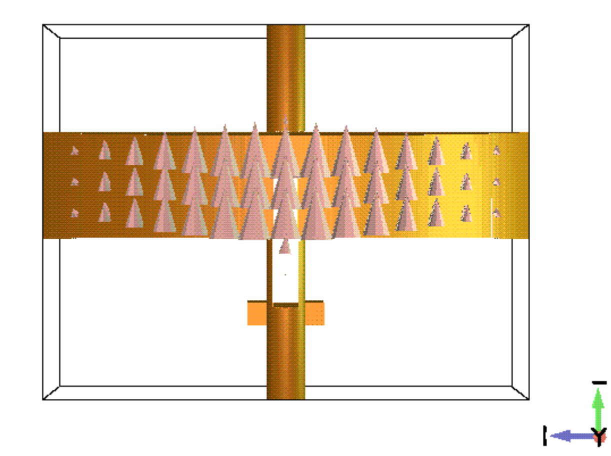

Figure 3: TM010-mode field pattern.

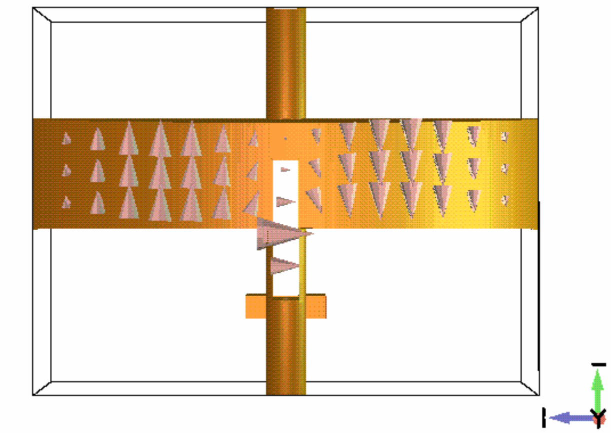

Figure 4: TM110-mode field pattern.

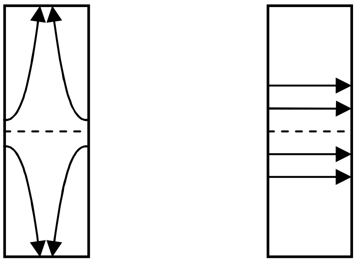

Figure 5: Electric field of the common (left) and the dipole mode (right) in the slot.

The most serious problem of the slotted cavity BPM is asymmetry, caused by non-ideal geometry. Because of the asymmetry in the field pattern with respect to the slot, the common mode can also couple to the TE10-wave. This imposes hard demands to the cavity production tolerances.

2 SLOTTED CAVITY BPM

2.1 Cavity Design

The frequency was chosen as 1.5MHz, a compromise between cavity size and prises of the electronic components.

The parameters of the slotted cavity were at first calculated roughly, using the pillbox simplification. Then, the whole geometry with slot and output waveguides were simulated by means of the Gdfidl code [4]. All cavity dimensions are matched then in the way that the R/Q-ratio has the highest possible value and the common mode frequency is far from bunch repetition frequency harmonics to avoid resonance.

The coupling into output waveguides is strong enough to provide the required signal-to-noise ratio and a short damping time for bunch-to-bunch measurements. The parameters of the cavity are listed in Table 1.

Parameter	**TM010**	**TM110**
f, MHz	1010	1518
Q_0	2110	1680
Q_{ext}	$\rightarrow\infty$	820
R/Q, Ohm	144	0.21/mm
BW, MHz	---	2.8
Decay time, nc	662	115
V_{out}, mV	9.3/100µm slot shift	0.056/100nm beam offset
V_{angle}/V_{offset}	---	34
V_{noise}, µV	---	1.6

Table 1: Cavity parameters.

2.2 Signal Estimation

The output signal voltage of the dipole mode can be estimated, if the $(R/Q)_{110}$ is calculated for some fixed offset from the axis.

The dipole mode voltage V_{out} relates to the output power P_{out} as:

$$V_{out}^{110}=\sqrt{ZP_{out}^{110}} \tag{2}$$

where Z is the output line impedance.

The output power relates to the external Q-value as:

$$P_{out}^{110}=\frac{\omega_{110}W_{110}}{Q_{ext}^{110}} \tag{3}$$

where W_{110} is the energy, stored in the dipole mode

The bunch, travelling along the axis with an offset δx gives the dipole mode the energy proportional to the shunt impedance, measured at the fixed offset δx_{fix}:

$$W_{110}=\frac{\omega_{110}}{2}\left(\frac{R}{Q}\right)_{fix}^{110}q^{2} \tag{4}$$

Then, substituting consequently (4) in (3) and (3) in (2) and assuming a linear dependence of voltage and offset, we get the voltage for any offset δx:

$$V_{out}^{110} = \pi f_{110}\sqrt{\frac{2Z}{Q_{ext}^{110}}\left(\frac{R}{Q}\right)_{fix}^{110}}\,\frac{\delta x}{\delta x_{fix}}\,q \qquad (5)$$

In order to estimate the common mode propagation, the cavity is simulated with the slot shifted from its original symmetrical position. The problem of this estimation is that the common mode external Q-value is very high, and the common mode signal cannot be estimated in the same way as the dipole mode signal. That is why the electric field intensity is calculated for both modes at the waveguide front-end, and then the common mode voltage is calculated using their ratio. From the numbers of Table 1 one can see, that if the slot is shifted, then the common mode signal is sensible. However, this does not bring any problem, because the common mode signal at the dipole mode frequency is at least 60dB less. To prevent the BPM electronics from the common mode leakage on its own frequency (1GHz), the cut-off frequency of the output waveguides is chosen to 1.3GHz – so, that the common mode does not propagate.

2.3 Angle-dependent Component

Angle-dependent component of the dipole mode is exited then the bunch trajectory is not parallel to the cavity axis. This situation takes place in the foreseen spectrometer scheme (Fig.1). There the bunch travels through the cavity with an angle of 0.5mrad.

The angle-dependent component excitation with respect to offset dependent component excitation is estimated as [5]:

$$\frac{\Delta V_{angle}^{110}}{\Delta V_{offset}^{110}} \approx i\,\frac{\theta}{kr_0}\left(1-\frac{kl}{2}\,ctg\,\frac{kl}{2}\right) \qquad (6)$$

For 0.5mrad angle and 100nm offset this ratio is around 34 (Table 1). To suppress the angular component one can use synchronous detection in electronics. With the phase error of the reference signal less than 1.7^0 the angle-dependent component is suppressed. This value seems to be hard to achieve, but 5^0, which is more realistic, provides the resolution of 300 nm. To achieve a better resolution, one can either use very stable electronic components or change the spectrometer in order to decrease the angle.

3 SIGNAL PROCESSING

The signal processing electronics is shown in Fig.5. It is based on the homodyne principle: The input signal is at first filtered in a Band Pass Filter (BPF) to suppress unwanted harmonics. Then it is down-converted using the LO-signal with the same frequency by an I/Q(in-phase/quadrarure)-mixer. The LO-signal is delivered from an additional reference cavity, with the common mode frequency equal to the dipole mode frequency of the monitor cavity. The synchronisation of the detection is adjusted with the phase shifter. The reference cavity signal serves also for charge measurements.

Actually, the electronics covers the dynamic range equivalent to 100nm minimum and 425μm maximum offset, which is not small, but not enough to measure around 5mm beam offset, for which a precise mover for the cavity should be used.

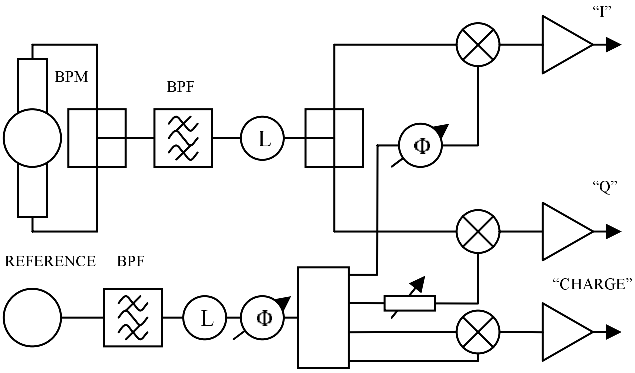

Figure 6: Signal processing electronics block-scheme.

4 CONCLUSION

The slotted cavity geometry is promising with respect to common mode rejection and hence the resolution. However, the resolution is limited by angle-dependent component excitation and can be improved, for example, by changing the spectrometer scheme. The further research will be oriented on solving this problem and the dynamic range extension in order to simplify the spectrometer construction and satisfy all its particular demands.

5 ACKNOWLEDGEMENTS

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