

BEAM DIAGNOSTICS BASED ON HIGHER ORDER MODE FOR HIGH REPETITION BEAM*

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Abstract

The signals from the HOM ports on superconducting cavities can be used as beam position monitors. The HOM amplitude of dipole mode is proportional to the beam offset. For high repetition bunches operation, the spectrum is consist of the HOMs peaks and the peaks which is integer times of the bunch repetition. The HOMs amplitudes should be separated from the two kinds of peaks. Based on the simulation from a TESLA 2-cell cavity, the transform matrix between the HOMs amplitudes and beam offsets has been found, as well as the cavity axis. The simulation results have demonstrated that beam diagnostics based on HOMs is feasible while high repetition bunches operation.

INTRODUCTION

Higher order modes (HOMs) will be excited when the charged particle beam goes through an accelerating cavity, which are one of the main causes of emittance growth and accelerating gradient decrease in an rf superconducting accelerator[1]. An effectual solution is to use HOM coupler to transfer the HOMs' power outside and then to be damped.

Meanwhile, the HOMs contain information about the beam, such as the arrival time of the beam, the offset position, the repetition frequency (f_{rep}), and so on. Once the transform relationship between HOMs and beam are found, these harmful HOMs can be used for beam diagnostics. Unlike traditional beam diagnostic with BPM, the beam diagnostics based on HOMs get the beam offset relative to cavity. Since the HOMs couplers and signal transfer components already exist, only electronics for signal analysis are needed, which means the cost would be low.

Superconducting technology is increasingly used for accelerators, in applications of free electron lasers, energy recovery linacs, and colliders, such as ILC, XFEL, FLASH, etc[2]. These projects all share the same design of accelerating cavity, based on the TESLA 9-cell cavity technology. DESY have accomplished the experiment of single bunch diagnostic based on HOMs measurement on TTF cryomodule, and reached a high precision [3]. In this paper, the HOMs excited by high repetition beam have been simulated by using a TESLA 2-cell cavity model. The transform relationship between HOMs and beam has also been found.

RESPONSE OF HOMs TO BEAM

The HOMs excited by charged particle bunch can be divided into several types[4]:

1) Monopole mode. Its amplitude $V_q = \frac{\omega_n R}{2Q_0} q$, where q is the bunch charge, ω_n is eigenfrequency of the mode, R and Q_0 are the mode's shunt impedance and unloaded quality factor. Its phase are determined by the arrival time of the bunch.

2) Dipole modes. The amplitude of the dipole modes excited by a bunch position offset is $V_q = C_x q x$, where x is the position offset relative to the mode center and C is a coupling constant determined by R/Q_0 and ω_n . Dipole modes are also excited by a bunch which traverses the cavity at an angle, or a tilted bunch. But they are not considered in the discussion below.

3) Quadrupole mode, etc.

We consider a train of bunches spaced in time by T_b , the ω_n mode field will store increasingly according to the equations below:

$$\text{While } 0 \leq t < T_b, \quad \tilde{V} = V_q e^{-\frac{t}{T_d}} e^{i\omega_n t}$$

$$\text{While } T_b \leq t < 2T_b, \quad \tilde{V} = V_q \left(1 + e^{\frac{T_b}{T_d}} e^{-i\omega_n T_b} \right) e^{-\frac{t}{T_d}} e^{i\omega_n t}$$

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$$\text{While } nT_b \leq t < (n+1)T_b, \quad \tilde{V} = \frac{V_q}{1 - e^{\frac{T_b}{T_d}} e^{-i\omega_n T_b}} e^{-\frac{t}{T_d}} e^{i\omega_n t}$$

Where V_q is the voltage of the mode excited by single bunch, T_d is the decay time of the mode. the beam repetition frequency is assumed to be 54.17MHz (1/24 of 1.3GHz), so $T_b = 18.46\text{ns}$. Assuming the ω_n is $2\pi * 1.81\text{GHz}$, corresponding with $TM_{110} \pi$ mode in TESLA 2-cell cavity, $T_d = \frac{2Q_1}{\omega_n} \approx 10^3\text{ns}$, the waveform and spectrum of \tilde{V} is showed in Figure 1 and Figure 2.

The resonance peak 1.81GHz can be seen in the spectrum of \tilde{V} . The other peaks are integer times of 54.17MHz, generated by the repetition of the bunches. Therefore, we should get rid of the distributions caused by these peaks, before the HOM peak analysis.

*This work was supported by a grant from the National High Technology Research and Development Program of China (863 Program) (No. 2009AA03Z206)

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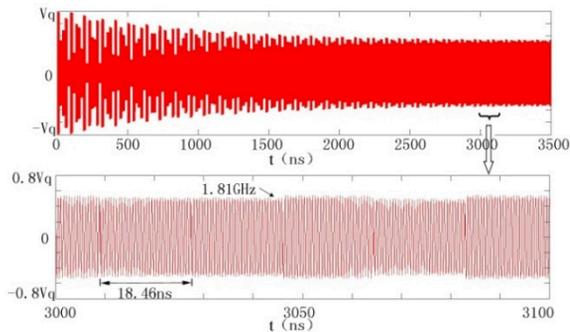


Figure 1: The waveform of one mode voltage caused by high repetition beam.

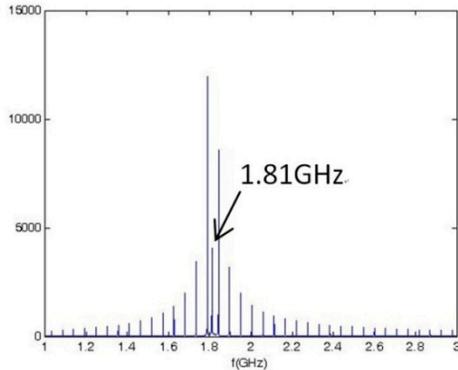


Figure 2: The spectrum of one mode voltage caused by high repetition beam.

SIMULATION OF SINGLE BUNCH OPERATION

The HOMs signal caused by a single bunch has been calculated in CST Partical Studio. In order to decrease the mesh numbers and the computer calculating time, a TESLA 2-cell cavity model was used instead of the TESLA 9-cell cavity, as shown in Figure 3. Its HOM coupler is the same as 9-cell cavity. The voltage of the HOM coupler pickup port (the red square in Figure 3) has been simulated. The bunch enters the cavity with a transverse offset $z=5\text{mm}$, the pickup signals are shown in Figure 4, as well as its spectrum distribution. The types of HOMs in Figure 4 are identified by comparing their frequencies to the simulation results in Ref.[5].

The mode $\text{TE}_{111} \pi/2$ and $\text{TM}_{110} \pi/2$ was chosen to be used in beam diagnostics, because of their larger amplitude.

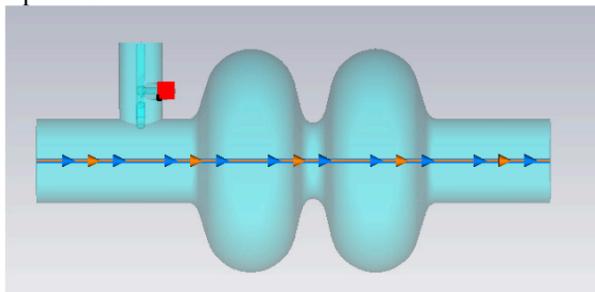


Figure 3: The TESLA 2-cell cavity model used for simulation.

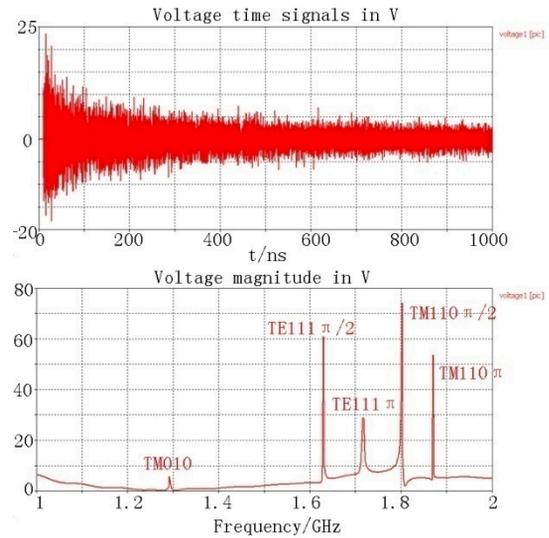


Figure 4: The simulation results of the HOMs excited by a single bunch.

SIMULATION OF HIGH REPETITION BUNCHES OPERATION

The HOMs signal caused by a train of high repetition bunches has also been calculated in CST Partical Studio. The repetition frequency was set as 54.17MHz, and the average current of the beam is 10mA. The voltage of HOM coupler pickup port, while beam offset is $z=5\text{mm}$, is shown in Figure 5, as well as its spectrum distribution.

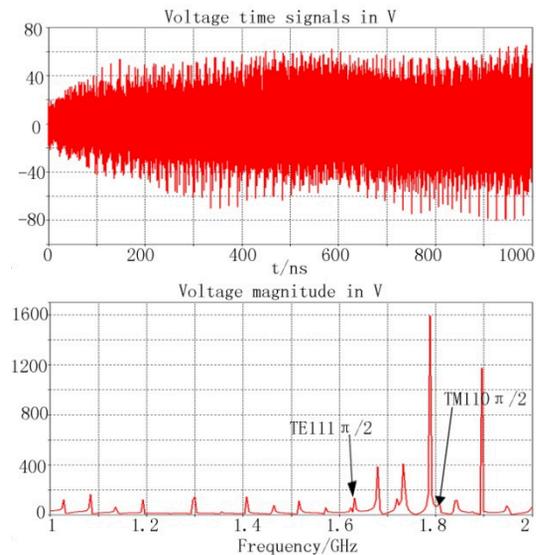


Figure 5: The simulation results of the HOMs excited by high repetition bunches.

To remove the distribution of the peaks at integer times of 54.17MHz, the amplitude of the HOMs are deemed as the value in Figure 6.

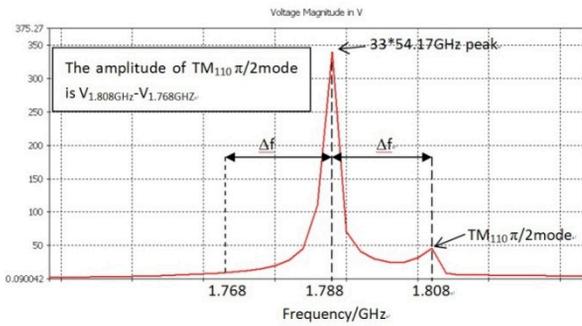


Figure 6: The HOMs amplitudes are found with both kinds of peaks.

After simulating the HOMs signals caused by different offset beam, the amplitude of $TE_{111} \pi/2$ and $TM_{110} \pi/2$ are shown in Table 1. Note that the amplitudes and the beam offsets are demonstrated to have a good linearity.

Table 1: The HOMs Amplitudes Excited by Beam with Offsets from 1mm to 5mm

Y/mm	Z/mm	$TE_{111} \pi/2$ mode/V	$TM_{110} \pi/2$ mode/V
0	5	112.1681	84.98772
0	4	81.72214	64.5639
0	3	53.45532	45.32876
0	2	26.22209	26.74973
0	1	-2.01223	8.35862
1	0	23.28881	6.872843
2	0	65.44579	20.379
3	0	104.9339	33.4704
4	0	144.3772	46.72476
5	0	186.0412	60.9116

Because of their good linearity, the relationship between the beam offsets and amplitudes can be written as below:

$$[y \ z] = [V_1 \ V_2 \ 1] \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \\ A_{31} & A_{32} \end{bmatrix}$$

The matrix A is the transform matrix. According the data in Table 1, the matrix A turn out to be:

$$A = \begin{bmatrix} 0.0449 & -0.0342 \\ -0.0643 & 0.1031 \\ 0.4922 & 0.1167 \end{bmatrix}$$

Note that while $V_1=V_2=0$, we can get $(y_0, z_0)=(0.4922, 0.1167)$. It means the energy of these two modes is minimum when the beam enter the cavity with this offset (y_0, z_0) , which is the cavity axis.

Matrix A can be used to calculate the beam offset positions from HOMs amplitudes. The rms precision is 70um in y and 30 um in z. Besides the simulation errors, the main cause of errors is that Matrix A comes from only ten groups of data. If more data could be used in calibration, the errors would decrease sufficiently.

DESIGN OF EXPERIMENTAL FACILITY

The simulation results have demonstrated that beam diagnostics based on HOMs is feasible while high repetition bunches operation. The future works will be focused on the experiment. The preliminary design of the

experimental facility would be similar to the single bunch experiment in DESY[2]. As shown in Figure 7, the beam is steered by the steering magnets. The HOMs caused by different offset beam are measured by HOM couplers and the electronics. The BPMs are used only for calibration. After the transform matrix A is found, the system can work alone without BPMs.

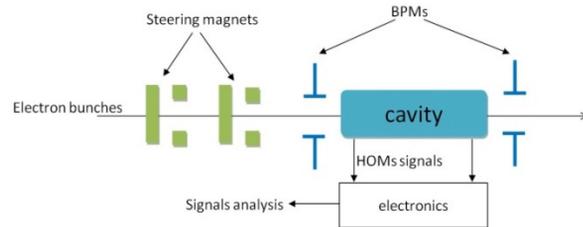


Figure 7: Preliminary design of the experimental facility.

CONCLUSIONS

The signals from the HOM ports on superconducting cavities can be used as beam position monitors. For high repetition bunches operation, the spectrum is consist of the HOMs peaks and the peaks which is integer times of the bunch repetition. The simulation results have demonstrated that beam diagnostics based on HOMs is feasible while high repetition bunches operation. The transform matrix between the HOMs amplitudes and beam offsets has been found from ten sets of data, and the rms errors are supposed to be 70um in y direction and 30 um in z. The errors would decrease sufficiently if more data could be used in calibration. These simulation works are supposed to be a helpful reference for the experience in future.

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