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AN EXPERIMENTAL STUDY OF HIGHER-ORDER MODES EXCITED BY HIGH REPETITION RATE ELECTRON BEAM IN AN SRF CAVITY*

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Abstract

Higher-order modes (HOMs) excited by electron beam traversing a superconducting rf (SRF) cavity contain lots of information and can be used for intra-cavity electron beam diagnostics. Unlike single bunch, multiple bunches would excite HOMs with a much complicated spectrum. In this paper, we present our recent research on HOMs excited by a high repetition rate electron beam in an SRF cavity. Especially, we focus on the integer multiple frequency peaks in the HOM spectrum, which are determined by the nearest eigen HOM peaks. The experiments were carried out on the DC-SRF photoinjector, which was operated at MHz repetition rate. The results agree well with theoretic analysis.

INTRODUCTION

Higher-order modes (HOMs) excited by electron beam travelling through a superconducting rf (SRF) cavity contain abundant information of the electron beam [1,2]. Lots of studies have been carried out for single electron bunch excited HOMs and the applications [2,3,4]. There are also some research on HOMs excited by multiple electron bunches [5,6], in which case, however, the characteristics of HOMs have not been well studied.

We recently studied HOMs excited by high repetition rate electron bunches, with the focus on HOM characteristics. Some preliminary experiments have been conducted on the DC-SRF photoinjector [7] at Peking University. In the following sections, we will first discuss the characteristics of HOMs excited by high repetition rate electron bunches. The HOM experiments on the DC-SRF photoinjector will then be introduced. Some preliminary test results with electron beam offset in the SRF cavity will also be presented.

HOM EXCITED BY HIGH REPETITION RATE ELECTRON BEAM

When high repetition rate electron bunches go through an SRF cavity, the excited HOMs may accumulate in the cavity, depending on the time interval between the bunches and the decay time of the modes. Considering a long train of electron bunches with the bunch charge of q, equally separated by T in time domain, the HOM voltage at the time t when the Nth bunch has passed through the cavity can be obtained using the superposition principle as [8]

$$V_N(t) = \sum_{n=0}^{N} V_q \cos[\omega_0(t-nT)]\, e^{-\frac{t-nT}{T_d}}, \quad (1)$$

where V_q is the HOM voltage excited by a single bunch, ω_0 and T_d are the frequency and decay time of the mode, respectively.

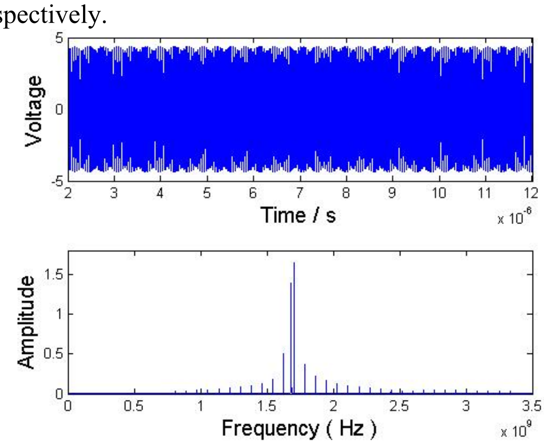

Figure 1: A typical waveform of HOM mode excited by a high repetition rate electron beam (upper) and its spectrum (lower). In the calculation, the repetition rate is assumed to be 81.25 MHz and the HOM frequency is assumed to be 1.685GHz.

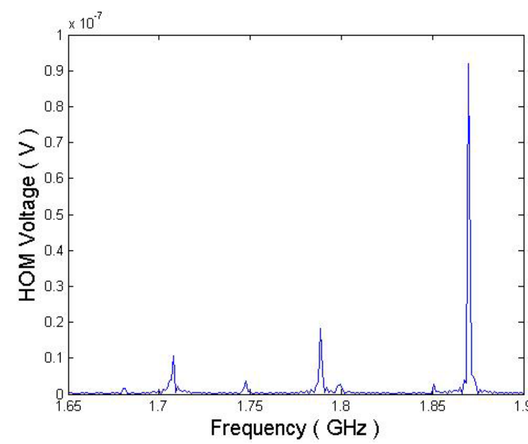

Figure 2: Simulated HOM spectrum, which is excited by a train of bunches at the repetition rate of 81.25MHz.

Figure 1 shows a typical waveform of HOM excited by a high repetition rate electron beam, calculated using Eq. (1), and its spectrum. It can be seen from the figure that the HOM spectrum is rather different to single bunch case [6]. Besides the peak at the HOM eigen frequency (referred to as eigen HOM peaks hereon), many other peaks can be observed at integer multiples of the bunch repetition frequency (referred to as IF peaks hereon).

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Such characteristics can also be observed from PIC simulation results, as shown in Fig. 2.

The IF peaks can be further investigated by looking into the Fourier Transform of the HOM voltage, Eq.(1), which turns out to be

$$F(\omega)=\frac{V_q}{T}\int_{NT}^{(N+1)T}\sum_{n=0}^{N}\cos\omega_0(t-nT)e^{-\frac{(t-nT)}{Td}}e^{-j\omega t}dt\,. \quad (2)$$

Considering that the IF peaks' frequencies are integer multiples of the bunch repetition frequency, i.e. $\omega T = 2m\pi$, and plugging in $T_d = 2Q_L/\omega_0$, where Q_L is the load quality factor of the HOM, Eq. (2) can be simplified as:

$$F(\omega)=\frac{V_q}{2m\pi}\frac{\frac{1}{2Q_l}\frac{\omega_0}{\omega}+j}{\left[\left(\frac{1}{4Q_l^2}+1\right)\frac{\omega_0^2}{\omega^2}-1\right]+\frac{j}{Q_l}\frac{\omega_0}{\omega}}\,. \quad (3)$$

In the case where Q_L is much greater than unity, the amplitude of IF peaks can be expressed as:

$$|F(\omega)|=\frac{V_q}{2m\pi}\left|\frac{\omega_0^2}{\omega^2}-1\right|^{-1}. \quad (4)$$

The equation indicates that the amplitude of IF peaks has a linear dependency on that of the nearest eigen HOM peaks. Therefore it can be used instead for HOM analysis to obtain a better signal to noise ratio, which is meaningful since the IF peaks can always be much stronger than the eigen HOM peaks. A detailed discussion on this will be presented elsewhere later.

HOM EXPERIMENTS ON DC-SRF PHOTOINJECTOR

Preliminary experiments have been carried out recently on the DC-SRF photoinjector, which comprises a DC Pierce gap and a 3.5-cell 1.3 GHz TESLA-type cavity. In the experiments, the photoinjector was operated in pulse mode, with a macro pulse length of a few milliseconds; the electron bunches in the macro pulse had a bunch length of less than 5 picoseconds and the repetition rate could be adjusted between 81.25 MHz and a few kHz.

The HOM characteristics of the 3.5-cell SRF cavity had been carefully investigated before experiments. A list of parameters for the first two dipole bands is shown in Table 1. At present, the feedthrough of HOM coupler has not been installed in the 3.5-cell SRF cavity. Therefore we extracted the HOM signal from the pickup port in our experiments, which has weak coupling to the cavity. The eigen HOM peaks in the extracted HOM signal was too small to be seen. However, the IF peaks were stronger and could be clearly observed, which were therefore used in our study instead of the eigen HOM peaks.

The HOM signal is measured by Agilent Real-time Spectrum Analyzer (RSA) N9030 [9]. Figure 3 shows an example of the measured HOM spectrum, in which the IF peaks can be clearly observed. This has a good agreement with the previous analysis.

Table 1: A List of Parameters for the First Two Dipole Bands of the 3.5-cell SRF Cavity of DC-SRF Photoinjector

	CST MWS Results		**Measurement Results**
mode	f(MHz)	R/Q	f(MHz)
$TE_{111}(\pi/4)$	1634.35	0.07	1644.352
$TE_{111}(\pi/2)$	1681.53	2.49	1686.998
$TE_{111}(\pi/2)$	1681.53	2.49	1688.468
$TE_{111}(3\pi/4)$	1747.03	10.07	1750.060
$TE_{111}(3\pi/4)$	1747.03	10.07	1752.247
$TM_{110}(\pi)$	1798.05	3.43	1794.627
$TM_{110}(\pi)$	1798.05	3.43	1796.939
$TM_{110}(3\pi/4)$	1849.61	3.47	1844.417
$TM_{110}(3\pi/4)$	1849.61	3.47	1860.065
$TM_{110}(\pi/2)$	1872.20	1.42	1870.183
$TM_{110}(\pi/2)$	1872.20	1.42	1872.142
$TM_{110}(\pi/4)$	1883.84	0.77	1880.949
$TM_{110}(\pi/4)$	1883.84	0.77	1884.458

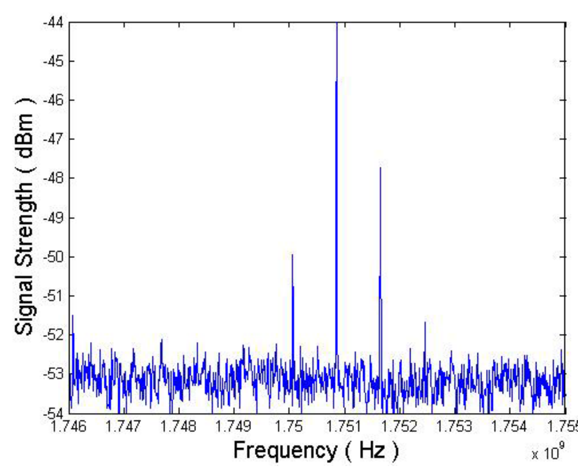

Figure 3: An example of measured HOM spectrum for the 3.5-cell SRF cavity of DC-SRF photoinjector.

Among the HOMs, dipole modes are related to beam position and therefore are more concerned in our study. We measured the IF peaks around all the eigen HOM peaks in the first two dipole bands. The measurements were performed under four different values of bunch repetition rate, i.e. 16.25 MHz, 0.797 MHz, 0.406 MHz, and 0.322 MHz. The results are shown in Table 2. From the table, one can see that the IF peaks related to $TE_{111}(3\pi/4)$, $TM_{110}(\pi)$, and $TM_{110}(3\pi/4)$ have all been detected in the four cases. This is consistent with the results in Table 1, where these modes have the largest R/Q values.

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Dipole modes have two polarizations, corresponding to two transverse orthogonal polarizing directions. They always have different frequencies due to imperfect fabrication of SRF cavity and introduction of end group. For example, in our case, the frequency difference for some dipole modes may be close to 3 MHz (see Table 2). This may lead to trouble in some applications based on HOM measurements [2]. This problem can be overcome when the bunch repetition rate is high, in which case IF peaks with the same frequency can be found for the two polarizations, as can be seen in Table 2.

Table 2: Measurement results of HOMs excited by high repetition rate electron bunches. Four tests have been performed, referred to as Case 1, Case 2, Case 3, and Case 4 herein, with the bunch repetition rate of 0.322 MHz, 0.406 MHz, 0.797 MHz, and 16.25 MHz, respectively.

	CST MWS	**RF Measurement**	**Electron Beam excited HOMs in Experiments**			
			Case 1	Case 2	Case 3	Case 4
mode	f(MHz)	f(MHz)	f(MHz)	f(MHz)	f(MHz)	f(MHz)
$TE_{111}(\pi/4)$	1634.35	1644.352	-	1645.281	-	-
$TE_{111}(\pi/2)$	1681.53	1686.998	1684.744	-	1684.968	1690.386
$TE_{111}(\pi/2)$	1681.53	1688.468	1685.538	-	1684.968	1690.386
$TE_{111}(3\pi/4)$	1747.03	1750.060	1750.86	1754.182	1751.388	1755.401
$TE_{111}(3\pi/4)$	1747.03	1752.247	1750.86	1754.182	1751.388	1755.401
$TM_{110}(\pi)$	1798.05	1794.627	1798.65	1801.317	1798.780	1787.908
$TM_{110}(\pi)$	1798.05	1796.939	1798.65	1801.317	1798.780	1787.908
$TM_{110}(3\pi/4)$	1849.61	1844.417	1865.57	1868.770	1865.845	1852.923
$TM_{110}(3\pi/4)$	1849.61	1860.065	1865.57	1868.770	1865.845	1852.923
$TM_{110}(\pi/2)$	1872.20	1870.183	1875.92	-	-	-
$TM_{110}(\pi/2)$	1872.20	1872.142	1875.92	-	-	-
$TM_{110}(\pi/4)$	1883.84	1880.949	-	1887.462	-	-
$TM_{110}(\pi/4)$	1883.84	1884.458	-	1887.462	-	-

TESTS WITH ELECTRON BEAM OFFSET IN THE SRF CAVITY

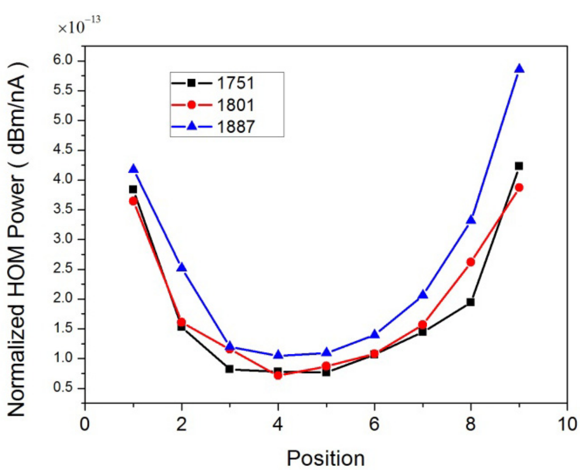

Figure 4: Normalized power of IF peaks at various beam offset in the SRF cavity. Position number is used as the horizontal coordinate instead of the beam positon since the absolute position has not been calibrated.

It is well known that dipole voltage excited by electron bunch has a linear dependency on the offset of electron beam [2]. To validate our observation on HOMs excited by high repetition bunches, we roughly scanned the position of the electron beam in the SRF cavity and measured the amplitude of IF peaks close to $TE_{111}(3\pi/4)$, TM_{110} (π), and TM_{110} ($\pi/4$). The results are plotted in Fig. 4, which shows that the IF peaks grow when the electron beam deviates from the center of the cavity, as can be expected.

SUMMARY

HOMs excited by high repetition rate electron bunches have been studied in this work. Especially, the IF peaks in the HOM spectrum, which is determined by the nearest eigen HOM peaks, have been investigated in detail. The theoretic analysis and experiment results agree well. Some preliminary tests have also been carried out by offsetting the electron beam in the SRF cavity. The result turn out to be consistent with the work on single bunch excited HOMs.

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