Design and studies on the traveling wave transverse RF deflecting structure*

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Abstract With the development of free electron laser (FEL) and the international linear collider (ILC), the electron bunch length is getting smaller and smaller. The traveling-wave transverse RF deflecting structure is an important part of the RF deflecting method for bunch length measurement and phase space diagnostics. The operation mode in RF deflector is the "TM_{11}-like" mode. Since the TM_{11}-like mode in this structure has a pair of degenerate dipole modes, two additional holes are provided on either side of each iris to stabilize the mode. The simulation and optimization have been done. A prototype has been fabricated and tested. The cold test results have been compared with the simulations of the first three modes.

Key words TM_{11}-like mode, RF deflector, mode stabilizer, vertical polarized wave, parallel polarized wave

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1 Introduction

With the development of free electron laser (FEL) and the international linear collider (ILC), the electron bunch length is getting smaller and smaller[1]. The ultra-short bunch length's measurement becomes an important technology in the world. There are several ways to measure such short bunch lengths[1, 2], such as the electro optic techniques, the zero-phase crossing measurements, the coherent radiation from a short bunch, RF deflecting cavity method and so on. Measuring very short bunches with RF deflecting cavity is an important method which is investigated and developed at many labs. It is the first real 'longitudinal/transverse correlation monitor' system. Furthermore, the X-ray FELs will require the ability to observe variable electron beam characteristics, such as the emittance and peak current, within the bunch length.

At SLAC, an old RF deflecting structure which was fabricated in mid 1960's[3] was used to do some experiments[4], and the situation at DESY[5] is similar. In a word, the experiments have testified that using RF deflector to measure the micro-bunch lengths in future FELs and ILC is quite promising. It is an advanced, reliable and economical method.

2 Principle

The transverse RF deflecting cavity is an iris-loaded waveguide structure. We choose the traveling wave structure simply because it is better under normal conditions[6]. It will be operated at 2856 MHz because high power klystrons and other equipments are readily available in our lab. Compared with other modes, $2\pi/3$ mode will give the largest deflecting efficiency[6]. So a $2\pi/3$ phase shift per cell has been chosen. It works in backward-wave type mode. The deflecting mode in the iris-loaded cylindrical waveguides is TM_{11}-like or HEM_{11}mode. For the polarization degeneration, minor imperfections in the structure could cause the mode to rotate. Two additional holes are provided to stabilize the mode and prevent rotations.

2.1 TM_{11}-like mode

"TM_{11}-like" mode is also called HEM_{11} mode. It is a hybrid electromagnetic mode. In the longitudi-

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nal direction it has E_z as well as H_z component. In fact, in the central region, i.e. $r \leqslant a$, it is composed of TE_{11} and TM_{11} modes. As TM_{11}-like mode is the main reason of the beam break-up (BBU), it has been widely studied[6, 7]. H. Hahn[8, 9] and Y. Garaault had made extensive analytical studies. By Fourier's analyses of the fields which are in an iris-loaded structure, the first order solution for the lowest order deflecting mode at $v_p = c$ in cylindrical coordinates is obtained as the following[10].

$$\begin{aligned}
E_z &= E_0 kr\cos\theta, \\
E_r &= E_0\left[\left(\frac{kr}{2}\right)^2 + \left(\frac{ka}{2}\right)^2\right]\cos\theta, \\
E_\theta &= E_0\left[\left(\frac{kr}{2}\right)^2 - \left(\frac{ka}{2}\right)^2\right]\sin\theta, \\
Z_0 H_z &= -E_0 kr\sin\theta, \\
Z_0 H_r &= -E_0\left[\left(\frac{kr}{2}\right)^2 - \left(\frac{ka}{2}\right)^2 + 1\right]\sin\theta, \\
Z_0 H_\theta &= E_0\left[\left(\frac{kr}{2}\right)^2 + \left(\frac{ka}{2}\right)^2 - 1\right]\cos\theta.
\end{aligned} \tag{1}$$

where $k = 2\pi/\lambda$ is the free-space wave number, a is the radius of the iris aperture, Z_0 is the free-space impedance, $E_0 = |E_0|e^{ik(z-ct)}$ represents a traveling wave, and c is the light speed.

2.2 Mode stabilizers and couplers

For the perfect RF cavity, there is a pair of degenerate dipole modes. In order to obtain the needed polarization, the cavity geometry has to be perturbed to push up the frequency of the unwanted polarization mode, and align the required mode in a selected orientation. Because minor imperfections in the structure could cause the mode to rotate, two additional holes are provided to stabilize the mode. It is called mode stabilizer. There are three kinds of mode stabilizer[6]. The first one uses two lateral flats for its cylindrical waveguide using electroformed method at CERN. The other one uses two lateral rods at Brookhaven, since it uses brazing method for its cylindrical waveguide, this way is very convenient. The last one makes two small lateral holes in the disks at SLAC. Which method is to be adopted is based on machining arts and crafts. Different methods cause different dispersive relationships of the vertical and parallel polarization mode. We use two suppressor holes to prevent polarization plane rotation.

Relative to the connection-line of the two suppressor holes, the parallel polarization mode corresponds to θ=0°, and the vertical polarization mode corresponds to θ=90°. From Eq. (1), one can see that, for the vertical condition, E_z=0 in the holes. On the contrary, for the parallel condition, E_z obtains maximum value in the holes.

The couplers of the RF deflector are similar to those of the accelerating structures. The input and output cavities are coupled to the waveguides through rectangular windows. In order to compensate the field asymmetry caused by the windows, the two couplers should be 180° reversal.

In an iris loaded waveguide, the polarization plane of the TM_{11}-like mode is determined by the orientation of the input coupler. The connection-line of the two suppressor holes should be vertical to the coupler's direction for the vertical polarization mode is what we need. Fig. 1 shows the coupler and the suppressor's relative direction.

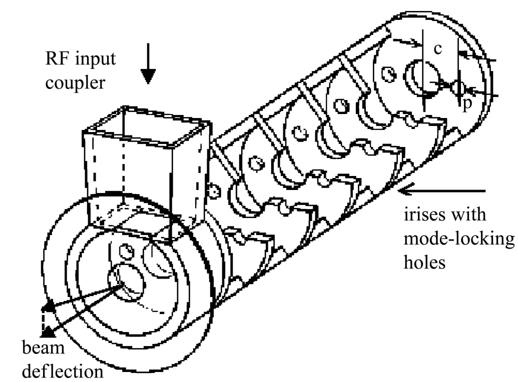

Fig. 1. The coupler and the suppressor's direction.

3 Design and measurement

Due to the existence of the suppressor holes, this structure is not cylindrical symmetric structure. 3D program is used to perform optimization. Some cold test models, see Fig. 2, were built for benchmarking the simulations against measurements.

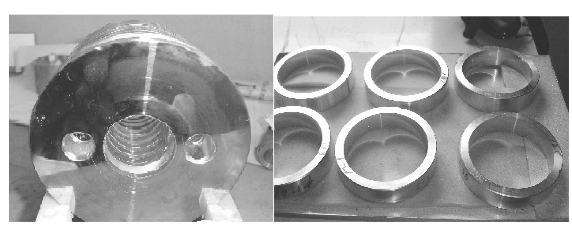

Fig. 2. The disks (left) and the cylindrical waveguides (right).

3.1 Optimization

The optimized dimensions of each cell (sketched in Fig. 3) are shown in Table 1, where a is the disk hole radius, b is the waveguide inside radius, D is the periodic length, t is the disk thickness, c is the suppressor holes offset, and p is the suppressor hole radius.

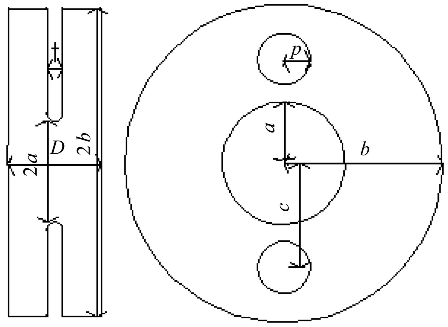

Fig. 3. Sketch of the single cell profiles.

Table 1. Optimized dimensions of the cells.

symbol	dimension/mm
a	22.44
b	58.17
D	35
t	5.84
c	38.1
p	9.525

Because the first three modes in this structure are all important for adjusting the RF deflector, the simulated data of TM_{01}, vertical polarization TM_{11}-like (TM_{11}-like (V)) mode and parallel polarization TM_{11}-like (TM_{11}-like (P)) mode are shown Fig. 4(a) to Fig. 6(b), respectively.

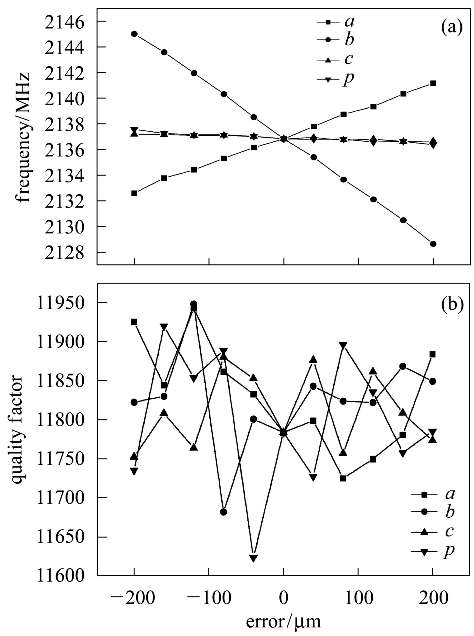

Fig. 4. (a) Relationship of TM_{010} mode: $\partial f/\partial a$=22 kHz/μm, $\partial f/\partial b$=−39 kHz/μm, $\partial f/\partial c$=−2.5 kHz/μm, $\partial f/\partial p$=−3.1 kHz/μm; (b) Quality factor vs. error of TM_{01} mode.

For the suppressor holes, the graph of frequency vs. dimension of the first three modes is not linear. Quality factors have not constant orderliness. From the result of differential coefficient, one can see that the frequency is not sensitive to the dimensions for this structure. Since The mode stabilizer in the direction of the parallel polarized wave direction, the vertical polarized wave and the parallel polarized wave have different signs vs. suppressor holes offset c.

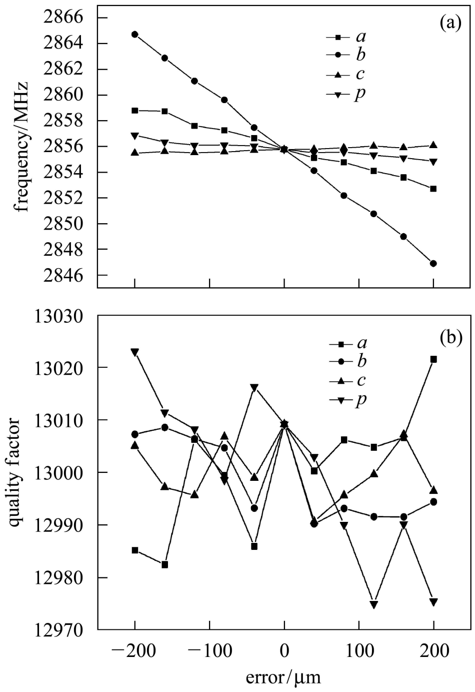

Fig. 5. (a) Relationship of TM_{11}-like (V) mode: $\partial f/\partial a = -14.78$ kHz/μm, $\partial f/\partial b = -46.24$ kHz/μm, $\partial f/\partial c = 2.27$ kHz/μm, $\partial f/\partial p = -5.07$ kHz/μm; (b) Quality factor vs. error of TM_{11}-like (V) mode.

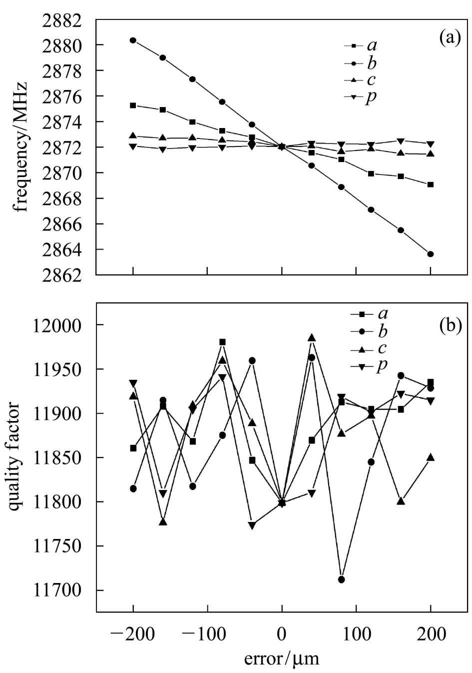

Fig. 6. (a) Relationship of TM_{11}-like (P) mode: $\partial f/\partial a = -21.09$ kHz/μm, $\partial f/\partial b = -42.56$ kHz/μm, $\partial f/\partial c = -2.49$ kHz/μm, $\partial f/\partial p = 3.4$ kHz/μm; (b) Quality factor vs. TM_{11}-like (P) mode.

3.2 Measurement

A clamp was used to connect the waveguides and disks for they were not brazed. Two coupling loops, shown in Fig. 7, were used to pick up the eigen modes. By adjusting the two coupling loops relative direction, the cavity chains of the first three modes, were obtained. Table 2 gives the eigen mode frequencies of different modes.

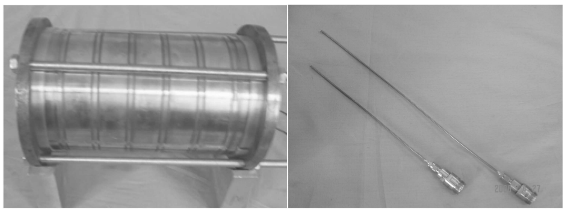

Fig. 7. The cavity prototype and the test coupling loops.

Table 2. Measurement data of eign mode.

operation mode	f/MHz		
	TM_{01}	TM_{11}-like(V)	TM_{11}-like (P)
0	2029.0	3103.6	3124.0
$\pi/6$	2039.9	2991.62	3014.0
$\pi/3$	2068.0	2918.88	2904.5
$\pi/2$	2106.0	2878.2	2900.0
$2\pi/3$	2141.0	2857.32	2878.9
$5\pi/6$	2165.0	2848.01	2870.04
π	2174.0	2845.3	2866.3

3.3 Comparisons of the simulation and measurement results

Figure 8 gives the simulated and measured dispersion curves of a stack of 5 cells (+2 half cells). The vertical polarized wave and the parallel polarized wave were detached due to the suppressor holes. From the graph one can see that TM_{11}-like mode works as a backward wave type in this structure. The simulated frequency difference of the vertical and the parallel polarization mode is 16.6 MHz. The measured one is 21.6 MHz. It can be said with certainty that there is only one mode operation.

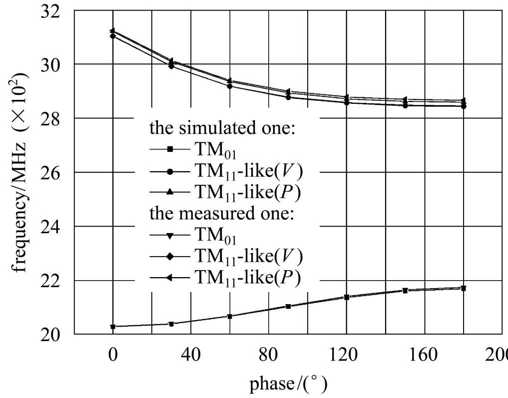

Fig. 8. ω-β diagram of simulation and measurement.

Table 3 shows the comparisons of the $2\pi/3$ TM_{01} mode, the TM_{11}-like (V) mode, and the TM_{11}-like (P) mode, respectively. The TM_{01} and the TM_{11}-like mode have different group velocities in this structure. They have reverse directions, and the value of TM_{01} is double that of the TM_{11}-like mode. Since the disks and the cylindrical cavities have not been brazed, the measured quality factor is lower than the simulated one.

Table 3. Comparisons between the simulated qualities and the measured ones of the first three modes.

mode		f/MHz	Q	v_g/c
TM_{01}	simulation	2136.7	12946	0.0404
	measurement	2141.0	9238	0.0413
$TM_{11}(V)$	simulation	2855.2	11638	−0.021
	measurement	2857.3	11816	−0.021
$TM_{11}(P)$	simulation	2871.8	11770	−0.022
	measurement	2878.9	11060	−0.021

4 Summary

From the simulated and the tested results, one can see that the test results are in agreement with the design predictions. The frequency of the cavity is not very sensitive to the dimensions. So the manufacture dimensions need not be very rigor. For the suppressor holes, the two degenerate dipole modes were detached.

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