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DESIGN OF A 3-CELL RECTANGULAR DEFLECTING RF CAVITY FOR A COMPACT THz-FEL*

Anlin Lei, Ruiying Luo, Qushan Chen†, Yongqian Xiong
State Key Laboratory of Advanced Electromagnetic Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, China.

Abstract

Bunch length is an important parameter for free-electron laser (FEL). The deflecting RF cavity was used in the beam length diagnostic instrument. In this paper, we present the design of a 3-cell rectangular deflecting RF cavity for a compact terahertz (THz) free-electron laser (FEL) facility. The 3-cell deflecting cavity has a residual orbit offset of zero as compared to single-cell deflecting cavity. Rectangular deflecting cavity does not need to lock the dipole polarisation direction as compared to cylindrical cavity. The time resolution of the measurement system can reach 500 fs. In this paper, the cavity design is carried out using CST and the results of cavity analysis are presented. Particle tracking is performed with the Astra code and the space charge effect is taken into account.

INTRODUCTION

A compact Terahertz free electron laser (THz-FEL) developed by Huazhong University of Science and Technology (HUST) [1] requires measuring the bunch length. The bunch length is an important parameter for free-electron laser (FEL). Currently, several techniques are employed for the measurement, including electrooptical sampling [2], streak camera [3], auto-correlation method [4], harmonic analysis [5], zero-phase cross [6], ponderomotive scattering [7], etc. The deflecting RF cavity is a popular solution in the field of ultrafast electron bunch detection due to its obvious advantages in system stability and universality.

In the case of a cylindrical symmetric cavity, two degenerate dipole modes are observed. In order to lock and maintain the dipole polarisation direction, coupling slots must be introduced in the wall between the cells [8]. In the case of the rectangular deflecting RF cavity, the design of the coupling slot is not a concern because there is no symmetry in the x- and y-directions.

For single-cell rectangular deflecting RF cavity, the addition of two cells on either side of the single-cell cavity results in the residual orbit offset (y-offset) of the reference particle is 0 [8]. Therefore, the 3-cell deflecting cavity has a zero-offset of reference particle as compared to single-cell deflecting cavity.

This paper presents a 3-cell rectangular deflecting RF cavity designed using CST with a resonant frequency of 2856 MHz in TM120 mode. The cavity exhibits a residual orbit offset of 0, a field flatness of 1. A maximum deflecting voltage is reached. The beam length measurement diagnostic system achieves a time resolution of 500 fs. The accuracy of the bunch length measurement diagnostic system is validated through the use of ASTRA. The impact of the space charge effect on bunch measurement is investigated.

THE BUNCH LENGTH DIAGNOSTIC MEASUREMENT SYSTEM

HUST THz-FEL requires a time resolution of 500 fs. In order to achieve this objective, it is necessary to design a system for measuring the length of the bunch. The system comprises a cavity, a drift, and a screen. The bunch enters through the cavity, and is finally imaged on the screen. The drift serves to amplify the effect of the scattering angle.

Deflecting Cavity Design

Based on the experimental conditions required for THz-FEL, the following constraints for designing the cavity can be obtained: (a) the maximization of the deflecting voltage; (b) the flat field distribution on the axis of the cavity; (c) the minimum residual orbit offset for the reference particles; (d) the cavity resonates at 2856 MHz in the TM_{120} mode.

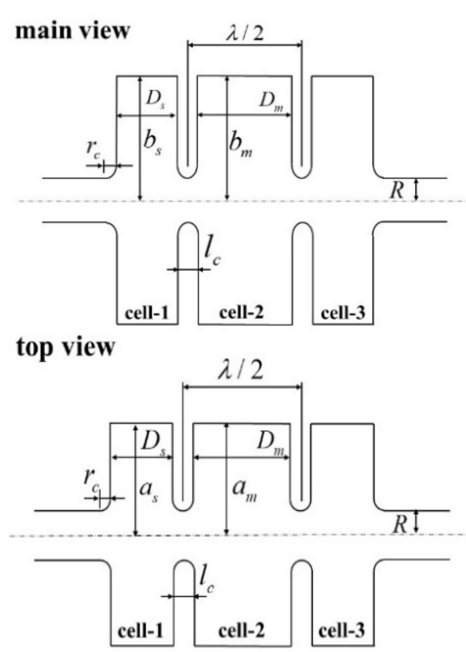

Figure 1: The relevant parameters in the 3-cell rectangular RF deflecting cavity.

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† email: chenqushan@hust.edu.cn

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In order for the cavity to be symmetrical in the longitudinal direction, it is necessary that the dimensions of cell-1 and cell-3 be identical. Consequently, the deflecting cavity has nine main parameters in Fig. 1. Due to the requirements of the π mode, the gap ($D_m + l_c$) of cell-2 is λ/2. The resonance frequency is greatly affected by cell-2, in the design of other constraints, do not adjust the dimensions of cell-2.

The deflecting voltage is a measure of the transverse kick of the deflecting cavity to the bunch as defines by Eq. (1):

$$V_T = E_\perp + \left(v \times B\right)_\perp \qquad (1)$$

According to Eq. (1), The deflecting voltage is primarily influenced by the magnetic field in the vicinity of the axis. In order to ascertain the maximum deflecting voltage, the dimensions as and bs of the cell-1 were scanned at various longitudinal lengths Ds. When Ds is varied within the range of 29.7 mm to 30.7 mm, the corresponding dimension as remain almost unchanged at around 97.27 mm. At this juncture, the alteration in bs exerts a nearly inconsequential influence on the deflecting voltage. By fixing the value of as to 97.27 mm, the effect of the deflecting voltage can be considered negligible when scanning Ds and bs.

It can be seen that changes in the Ds and bs of cell-1 will affect both the residual orbit offset (y/mm) and the field flatness (Bx;max;m/Bx;max;s). Consequently, it is essential to integrate the residual orbit offset and field flatness constraints in order to concurrently adjust the dimensions Ds and bs of cell-1. Fig. 2 depicts the residual orbital deviation of the reference particle for different values of (Ds; bs). Fig. 3 is analogous. In Fig. 4, the results of the simulation are presented in conjunction with straight lines with a reference particle residual orbit offset of zero and a field flatness of one. The meeting point of intersection represents the solution.

Fine-tuning the remaining free dimension brings the resonant frequency back to 2856 MHz and preserves the mode separation, and the simulation results are listed in Table 1. The cavity exhibits a resonant frequency of 2856 MHz in TM120 and π mode. The mode separation of π mode and π/2 mode is 6.73 MHz. The cavity achieves a quality factor of 16777 and a deflecting voltage of 1.75 MV at a peak RF power of 1.07 MW. The field flatness is 1.022, and the residual orbit offset is 0.09 mm. All the constraints are satisfied in the engineering.

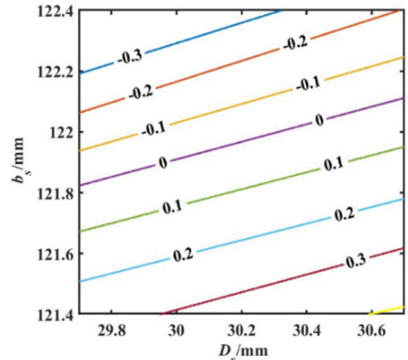

Figure 2: The residual orbit offset y (mm) under different (D_s; b_s).

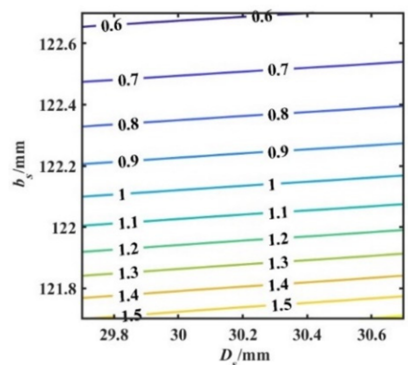

Figure 3: The field flatness $B_{x;max;m}/B_{x;max;s}$ under different (D_s; b_s).

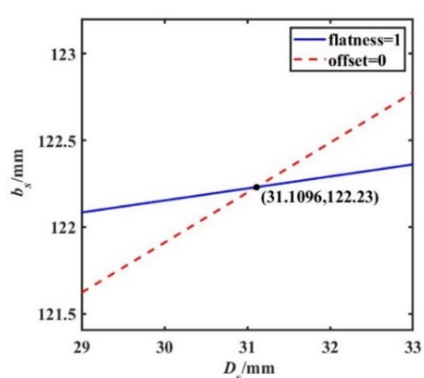

Figure 4: The meeting point at (31.11 mm, 122.23 mm) represents the work point for offset = 0 and flatness = 1 distribution simultaneously.

Table 1: Main Parameters and Simulation Results of the 3-cell Deflecting RF Cavity

Parameter	Value	Unit	Parameter	Value	Unit
a_m	104.47	mm	Q_0	16777	
b_m	119.46	mm	P_{in}	1.07	MW
a_s	97.27	mm	V_T	1.75	MV
b_s	122.23	mm	field flatness	1.022	
D_m	45.00	mm	orbit offset	0.09	mm
D_s	31.11	mm			
R	11.55	mm	f (π mode)	2856.00	MHz
l_c	7.50	mm	f (π/2 mode)	2862.73	MHz
r_c	1.99	mm	f (0 mode)	2872.85	MHz

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Layout Design

The parameters of the cavity, as determined by the design, are capable of satisfying the constraints imposed by HUST THz-FEL. The deflecting voltage is obtained through the design of the cavity. Eq. (2) and Eq. (3) represent the equations for bunch length and time resolution [9], respectively.

$$\sigma_z = \frac{p_z c}{q V_T \omega L}\sqrt{\sigma_{\rm on}^2 - \sigma_{\rm off}^2} \quad (2)$$

$$\sigma_t = \frac{p_z c}{q V_T \omega L}\sigma_{\rm off} \quad (3)$$

Where p_z is the longitudinal momentum of the particle and ω is the angular frequency of the deflecting field. When the deflecting cavity is open, the transverse rms dimension $\sigma_{\rm on}$ is obtained. $\sigma_{\rm off}$ is the same. Since the HUST THz-FEL requires a temporal resolution of 500 fs for the cavity, based on Eq. (3), the length of the drift should be 0.9 m.

PARTICLE TRACKING

The measurement system is designed to validate the principle of bunch length measurement using ASTRA for particle tracking. The electric and magnetic fields obtained from the CST simulation are presented in Fig. 5. Import the field into ASTRA and set the particle file according to the bunch of THz-FEL, as shown in Table 2.

The image of the bunch on the screen is depicted in Fig. 6. The calculated bunch length is 5.15 ps and the relative error is 3.0%. The measurement accuracy is sufficient to meet the requirements of time resolution.

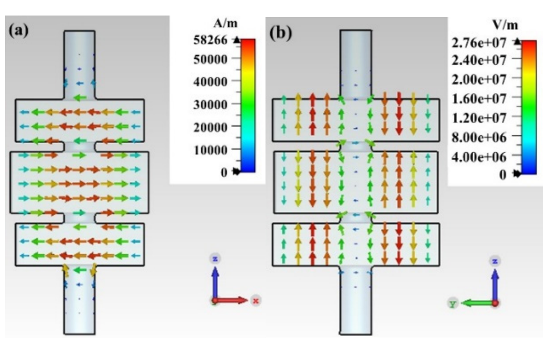

Figure 5: Cavity electromagnetic field distribution: (a) magnetic field distribution; (b) electric field distribution.

Table 2: Parameters of Bunch at the Entrance of the Deflecting Cavity

Parameter	Value	Unit
Electrical charge $Q_{\rm total}$	200	pC
Energy E	12	MeV
Energy dispersion $\delta\varepsilon$	0.5%	
Bunch radius r_{bunch}	1	mm
Emittance $\varepsilon_{\rm x}$	10	mm mrad
Emittance ε_y	10	mm mrad
Bunch length $\sigma_{\rm z}$	5	ps

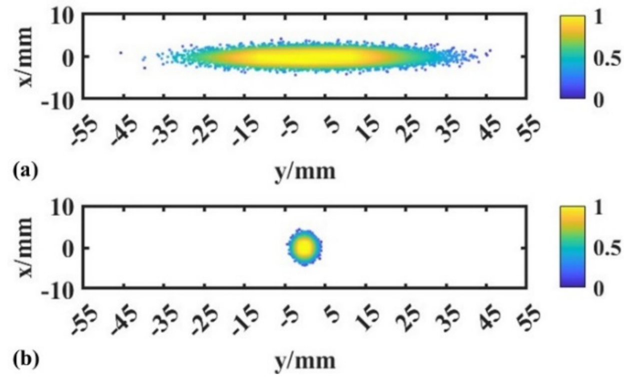

Figure 6: Transverse imaging of particles on the screen. (a) deflecting cavity on; (b) deflecting cavity off.

Additionally, the space charge effect may can also influence the measurement. The space charge effect causes $\sigma_{\rm on}$ to an increase of 0.03%, and it causes $\sigma_{\rm off}$ to increase 0.01%. The increase of $\sigma_{\rm on}$ is greater than the increase of $\sigma_{\rm off}$. According to Eq. (3), the measured beam length also increases by 0.02%. The influence of space charge effects is negligible in bunch length measurement.

CONCLUSION

This paper presents a 3-cell rectangular deflecting RF cavity designed for HUST THz-FEL to measure bunch length. The cavity exhibits a resonant frequency of 2856 MHz in TM_{120} mode and π mode. The cavity achieves a quality factor of 16777 and a deflecting voltage of 1.75 MV at a peak RF power of 1.07 MW. The field flatness is 1.022, and the residual orbit offset is 0.09 mm. The time resolution of 500 fs has been tested using ASTRA to ensure that it meets the requisite measurement requirement. The cavity meets the design constraints and measurement accuracy requirements.

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