ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO082

PHYSICAL DESIGN OF A RECTANGULAR RF-DEFLECTOR FOR ULTRA-SHORT BUNCH LENGTH MEASUREMENT*

J. Bai, Q. Chen, K. Fan†, State Key Laboratory of Advanced Electromagnetic and Technology, Huazhong University of Science and Technology (HUST), [430074] Wuhan, China

Abstract

Cylindrical deflectors which are now widely used for bunch length measurement suffer from the degeneration of polarization, while rectangular deflectors can separate polarization mode easily. This paper is focused on the study of a one-cell rectangular deflector, which is considerably different from cylindrical structure or multi-cell structure. A one-cell structure is free of π mode restriction and can achieve higher deflection efficiency per unit length. The proposed scheme is expected to achieve time resolution better than 200fs with the driving power less than 1MW. Cavity optimization and beam dynamic simulation are introduced in this paper.

INTRODUCTION

The linac-based terahertz free-electron laser (THz-FEL) facility with an independent tunable cavity (ITC) RF gun built in Huazhong University of Science and Technology (HUST) has undergone a long term beam commissioning [1]. One important reason is that there is no adequate beam diagnostic instruments due to the ultra-compact structure. In FEL, bunch length that defines the peak current is a critical parameter for the amplification process, but we still have not had an effective method to measure it accurately. Using RF deflector is an attractive method to measure bunch length in sub-picosecond level, while conventional cylindrical cavities suffer from degeneration of polarization due to their axial symmetry [2]. So we propose to use a rectangular structure with an aspect ratio not equal to 1. For 10 MeV electron beams and 1 MW driving power, the rectangular RF deflector system is targeted to be shorter than 1 m and is supposed to achieve time resolution better than 200 fs.

THEORY OF RF-DEFLECTOR SYSTEM

An RF-deflector imparts a transverse momentum on the bunch and directly relates the longitudinal bunch distribution into transverse one. The bunch length can then be inferred after measuring the downstream beam profile. According to the Panofsky-Wenzel theorem [3], the deflecting voltage is:

$$V_d = \int_h [E_\perp + (v \times B)_\perp] dz \,. \qquad (1)$$

Where h is cavity length along the beam direction (z-axis).

Considering a simple case in which there is only a drift between the deflector and the downstream screen, the bunch length can be computed as:

$$\sigma_t = \frac{p_z c}{qV_d L\omega}\sqrt{\sigma_{ys}^2 - \sigma_{yso}^2} \,. \qquad (2)$$

Where p_z is the longitudinal momentum of the electron bunch, L is the drift distance from the center of the RF-deflector to the downstream screen, c is the velocity of the light, σ_{ys} and σ_{yso} are the beam size on the screen with the deflector on and off, respectively. Temporal resolution σ_{t_res} is defined as:

$$\sigma_{t\_res} = \frac{p_z c}{qV_d L\omega}\sigma_{ys0} \,. \qquad (3)$$

For a specific electron beam and power source, higher deflecting voltage will result in better time resolution [4] The goal of the cavity design optimization is to find a cell geometry to maximize the deflecting voltage.

OPTIMIZATION OF THE CELL GEOMETRY

For the TM_{120} mode, there is no transverse electric field. According to Eq. (1), the analytical form of V_d can be expressed by,

$$V_d = \sqrt{\frac{2PQ\omega\varepsilon}{a^3bh}\frac{8\pi\mu_0 c}{k_c^3}}\sin(\frac{\omega h}{2v_z}) \,. \qquad (4)$$

Where a and b are the horizontal and vertical dimensions of the cavity, P is the power loss on the inner wall, Q is the quality factor of the cavity in TM_{120} mode, ε is the dielectric constant, k_c is the wave number, v_z is the particle velocity along the z axis. Eq. (4) is assumed as the basis for optimizing the cavity in this paper.

As for a rectangular cavity operated in the TM_{120} mode, the quality factor is determined by its geometry:

$$Q = \frac{2}{\delta}\frac{\int_v |H^2| dv}{\oint_s |H_\tau^2| ds} = \frac{1}{\delta}\frac{abh(a^2+4b^2)}{a^3(b+2h)+4b^3(a+2h)} \,. \qquad (5)$$

Where δ is the skin depth, H_τ is the tangential magnetic field of the cavity surface.

According to Eq. (5), Eq. (4) can be re-written as:

$$V_d = A\sqrt{\frac{(a^2+4b^2)}{a^5(b+2h)+4a^2b^3(a+2h)}}\sin(\frac{\omega h}{2v_z}) \,. \qquad (6)$$

* Work supported by the National Natural Science Foundation of China (No. 11705062) and the China Postdoctoral Science Foundation (No. 2018T110763).
† Email address: kjfan@hust.edu.cn

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO082

Where $A = \frac{8\pi\mu_0 c}{k_c^3}\sqrt{\frac{2P\omega\varepsilon}{\delta}}$.

What is more, there is a constraint of a and b because this cavity operates at 2856 MHz. Thus giving,

$$a = \frac{4}{\sqrt{(\frac{2f}{c})^2 - (\frac{1}{b})^2}} . \tag{7}$$

As mentioned in the previous section, our aim is to maximize the deflecting voltage. We use MATLAB for numerical optimization. Fig.1 shows the optimal a and the corresponding deflecting voltage Vd as a function of h. Based on the curve of the deflecting voltage, it can be simply thought that the value of h corresponding to the extreme point is the optimal solution. Then, the optimal solution of the value of a could be determined and the optimal solution of the value of b could be obtained by inverting Eq. (7). Finally, we conclude that for an ideal and closed rectangular cavity operated in TM120 mode, the optimal dimension to generate maximum deflecting efficiency is 120.59 mm × 106.64 mm × 46.96 mm (x×y×z).

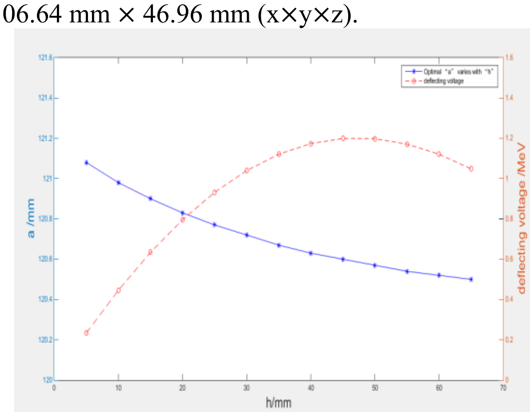

Figure 1: Optimal a and the deflecting voltage as a function of h, the power loss P is assumed as 1 MW.

CST SIMULATION

In practical applications, round corners, beam pipes, and couplers all affect the field distribution and the resonant frequencies of the cavity. In this section, the 3-D simulation software CST is used to adjust the parameters of the RF-deflector cavity and calculate the distribution of electromagnetic field and S-parameter. The left panel of Fig.2 shows the model of the RF-deflector.

The design of the coupler directly affects the efficiency of the feed power. The right panel of Fig. 2 shows a partial enlarged view of the coupling hole. Having consider the effect of a beam current of 0.2 A on the coupling coefficient in this standing-wave cavity, we find it makes better use of feed power when the reflection coefficient reaches -20.66 dB. For this reason, we changed the parameters of coupling hole to gain a suitable reflection coefficient and the optimal dimensions of the coupler is found to be 10.47 mm × 1.00 mm × 34.04 mm (x×y×z).

The magnitude and polar plot of S-parameter of RF-deflector cavity are shown in Fig. 3 and Fig. 4, respectively.

Finally, we simulated a practical open cavity operated in TM_{120} mode, the optimal dimension to generate maximum deflecting efficiency is 120.80 mm × 104.20 mm × 46.96 mm (x×y×z).

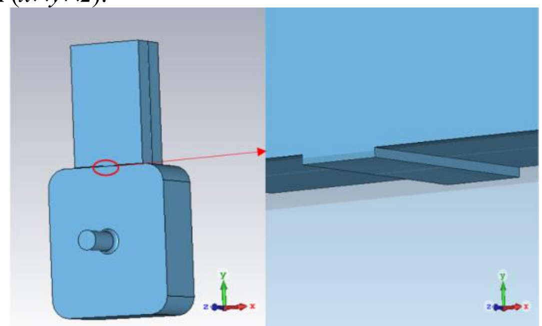

Figure 2: Structure of the RF-deflector cavity.

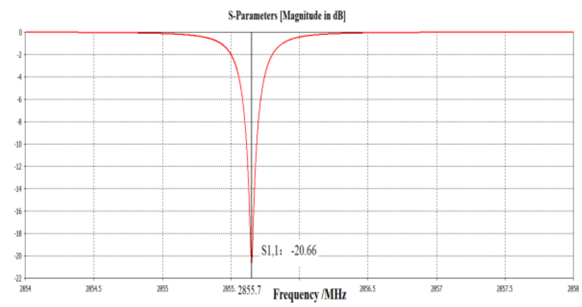

Figure 3: The magnitude of S-parameter of rf-deflector.

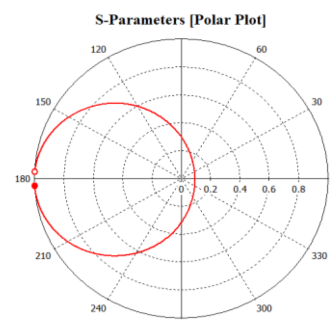

Figure 4: The polar plot of S-parameter of rf-deflector.

BEAM DYNAMICS SIMULATION AND ANALYSIS

Having imported the resonant field data produced by CST, we use Parmela to simulate the beam dynamics.

As mentioned above, when the beam energy is 10 MeV and the RF-deflector system is shorter than 1 m, our target is to achieve time resolution better than 200 fs with the driving power less than 1MW. The parameters of bunch are shown in Table 1.

According to Eq. (3), the calculated time resolution is 174.15 fs and meets our requirements. We used Parmela for particle tracking and for evaluation of the performance of the cavity. This electron beam is focused to a vertical beam size of 0.3 mm (RMS), and it will enlarge to 0.884 mm (RMS) when the RF-deflector is on. Figure 5 shows the transverse profile of the electron beam with the RF-deflec-

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO082

tor off and on, respectively. The parameters of RF-deflector are shown in Table 2. According to Eq. (2), the RMS bunch length is about 482.70 fs. There is a 0.70% deviation between our calculations and theoretical results (486.11 fs). Overall the RF-deflector system in principle meets the design requirements.

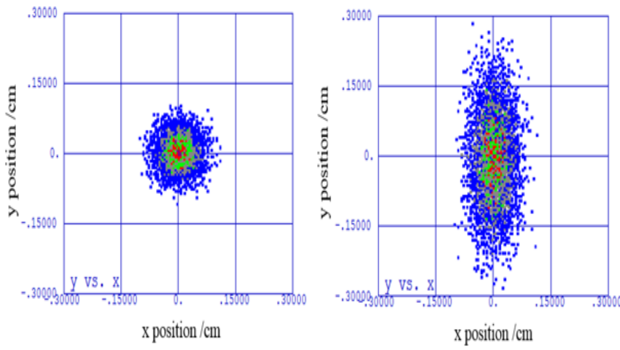

Figure 5: Transverse profile of the electron beam with the RF-deflector off (left) and RF-deflector on (right).

Table 1: Parameters of Bunch

Parameter	Value
Beam energy E [MeV]	10
Bunch length (RMS) [fs]	486.11
Change [pC/bunch]	100
Beam size σ_{yso} [mm]	0.3

Table 2: Parameters of RF-Deflector Design

Parameter	Value
Input rf-power Pin [MW]	1
Operation frequency f [MHz]	2856
Drift length L [m]	0.8
Deflecting Voltage V[MV]	1.20
Temporal resolution σ_{t_res} [fs]	174.15

CONCLUSIONS

In this paper, we introduced the basics of RF-deflector for sub-picosecond bunch measurement and obtained an optimal solution for the cavity size. We built a model of this cavity by 3-D simulation software CST, and calculated the distribution of electromagnetic field. For 10 MeV electron beams, the designed RF-deflector system, which is shorter than 1 m, achieves the time resolution better than 200 fs. Theoretical calculations have been verified by Parmela. In the future, we will install the RF-deflector system in the THz-FEL facility in HUST.

REFERENCES

[1] Q. Chen, et al., “Design of RF chopper system for improving beam quality in FEL injector with thermionic gun”, *Nuclear Inst. and Methods in Physics Research*, no. 755, pp. 78-84, 2014.
[2] Y. Nishimura, et al., “Design of a two-cell RF-deflector cavity for ultra-short electron bunch measurement”, *Nuclear Inst. and Methods in Physics Research, A*, no. 764, pp. 291-298, 2014.
[3] W. K. H. Panofsky and W. A. Wenzel, “Some considerations concerning the transverse deflection of charged particles in radio-frequency fields”, *Review of Scientific Instruments*, no.72, p.967, 1956.
[4] Y. Nishimura, et al., “Study on two-cell RF-deflector cavity for ultra-short electron bunch measurement”, in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPFI023, pp. 2753-2755.