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A NEW RF DESIGN OF THE TWO-MODE TRANSVERSE DEFLECTING STRUCTURE

H. Gong†, Z. Gao, Y. Guo, D. Su
Shanghai Institute of Applied Physics, Shanghai, China
W. Fang, X. Huang, J. Tan, C. Wang, Z. Zhao
Shanghai Advanced Research Institute, Shanghai, China

Abstract

SSRF (Shanghai Synchrotron Radiation Facility)/SXFEL (Shanghai Soft X-ray FEL) Facility has developed an advanced variable polarization transverse deflecting structure TTDS (two-mode transverse deflecting structure) to perform variable polarization based on the design of a dual-mode RF structure. The 15-cell prototype of the TTDS was fabricated at SSRF/SXFEL. Because the two modes operate in the same structure, any geometric change will affect both modes. A new RF design of the regular cell is proposed to improve rf performance. The two modes are coupled independently in two pairs of side coupling holes. The work presented in this paper is focused on the new design and the rf parameters compared with the initial design.

INTRODUCTION

Transverse deflecting structure (TDS) is a key part of accelerators which provides the particle beams with the transverse deflecting kick. It is widely used in accelerators such as beam measurement, particle separator, emittance exchange, collision angle compensation.

In recent years, several advanced applications based on TDS technology have been proposed for proton therapy and particle accelerators, two of which are currently under development as FLASH [1] and multidimensional beam tomography. FLASH is a new proton therapy technique with ultrahigh radiation dose rates averaging over 300 Gy/s and it requires an ultrafast switching of the beam path at 1ms. However, the conventional TDS can only deflect the beam transversely in a fixed polarized direction. Furthermore, by changing the deflecting direction, a TDS can extend the characterization in beam measurement from a single longitudinal length to a multidimensional reconstruction through the projection of the bunch distribution along any transverse axis [2].

Hence, variable polarization is now the research frontier of next-generation TDS development to meet the needs of the above experiments. Recently, a design called TTDS (two-mode transverse deflecting structure) was proposed and fabricated at SSRF/SXFEL to achieve the fast switching of bunches [3]. In that design, two deflecting modes, the HEM11 and HEM12 modes, which have mutually perpendicular polarizations, operate simultaneously in one structure. The structure is fed by two power sources, and the deflecting direction is controlled using an ultrafast low-level radio-frequency (LLRF) system [4] to realize ultrafast polarization control. The time scale for switching is equivalent to the switching speed of the LLRF system, about 100 ns to 1 µs. The dual-mode TDS can deflect beams in any polarized direction and can change the direction in an ultrashort time, therefore, it can perform the fast solid angle switching required by FLASH. However, both modes are coupled in the centre beam hole on the regular cell, which increase the difficulty of optimization in cell design and measurement after fabrication. Therefore, an improved design of the regular cell is proposed at SSRF/SXFEL.

The research discussed in this paper is focused on the redesign and comparison of the regular cell in TTDS. First the theory and component of the TTDS are discussed. After analysing the electromagnetic field distribution of the two modes, a new rf design of the regular cell is proposed. Finally, the rf parameters of the new regular cell is compared with the initial one in [3].

THEORY AND COMPONENT OF THE TTDS

As shown in Fig. 1, two traveling wave deflecting modes with perpendicular polarization directions are running in the TTDS at the same time, and the phase of the deflecting voltage is synchronized with the bunch, so that the bunch is subjected to a stable transverse deflecting force. By adjusting the magnitude and proportion of the deflecting voltages of the two modes, the beams can be deflected to any solid angle.

The layout of the TTDS system is shown in Fig. 1. The system uses two power sources at 2856 and 5712MHZ as input signals that enter the TTDS from two input ports through a dual-frequency coupler. The two input signals excite linearly polarized modes in the structure whose polarization directions are perpendicular to each other. The two modes will not be coupled because of the double frequency difference. At the output of the TTDS, another identical dual-frequency coupler separates the two modes into two output ports. Additionally, a bandpass filter is needed on the low-frequency port to prevent flow-through of the high-frequency signal.

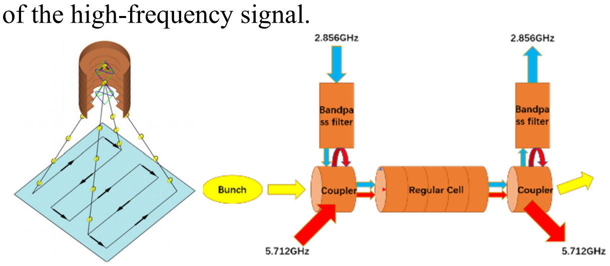

Figure 1: Schematic(left) and layout(right) of TTDS.

† gonghanyu@sinap.ac.cn

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Because the frequency of the HEM_{12} mode is nearly twice that of the HEM_{11} mode, this mode combination is more convenient in terms of the use of power sources. The HEM_{11} and HEM_{12} modes are selected as the operating modes in the vertical and horizontal directions, respectively. The phase advances selected in this design are $\varphi_{HEM11} = 2/5\pi$ and $\varphi_{HEM12} = 4/5\pi$.

The rf design of each component is given below. For clarity, the subscripts for the two modes are replaced by 1 and 2 instead of HEM_{11} and HEM_{12}.

Regular Cell

The conventional TDS adopts the constant impedance disk-load waveguide structure as regular cell and the HEM11 mode as the deflecting mode. This rf structure is also suitable for the HEM12 mode, so it is possible to run these two operating modes simultaneously in one regular cell. The cell shape is adopted as elliptic to tune the two modes simultaneously and separate the HEM modes from its degenerate mode to fix the polarized direction. The longitudinal electric field distribution of the two HEM modes is shown in Fig. 2.

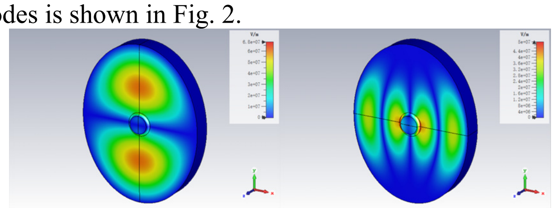
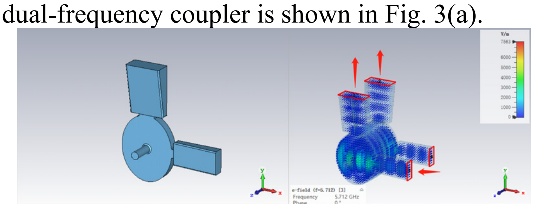


Figure 2: Longitudinal electric field distribution of the HEM_{11} (left) and HEM_{12} (right) mode.

Dual-frequency Coupler

From the point of view of compactness, for a two-mode operation TDS, the power of both frequencies needs to be fed into one coupling cell. Based on the conventional coupling cell, the cell shape is also adopted as elliptic and a similar coupling port is added on the cavity wall of the polarized direction of the HEM12 mode. The geometry of the dual-frequency coupler is shown in Fig. 3(a).



(a) (b)

Figure 3: (a) Geometry of the dual-frequency coupler (b) The electric field distribution of HEM_{12} mode in match.

Figure 3(b) shows the electric field distribution of the HEM_{12} mode after optimization. It can be seen that although the HEM_{12} mode is successfully excited, part of the power is output from the corresponding port of the HEM_{11} mode, which will lead to power waste and damage to the power source. Therefore, it is necessary to load a bandpass filter at the low-frequency port that allows S-band power to pass and blocks the C-band power.

Bandpass Filter

The geometry of the bandpass filter is shown in Fig 4. It is essentially a low-pass filter with standard rectangular waveguides of S-band at both ends, the disk-load structure in the middle can be equivalent to a pair of capacitors and inductors, and the entire isolator can be equivalent to a string of LC resonant circuits. For the passband, the centre frequency is 2856 MHz, the amplitude of S_{11} is −54.1 dB, and the bandwidth of −30 dB is 71 MHz. For the stopband, the centre frequency is 5712 MHz, and the amplitude of S_{12} is −89.1 dB.

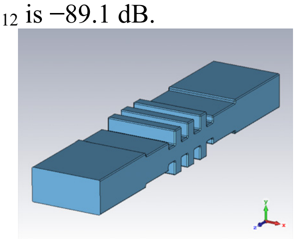


Figure 4: Geometry of the bandpass filter.

NEW REGULAR CELL DESIGN

In the regular cell, if only the centre beam hole is used for coupling between cells, the two deflecting modes will share a single coupling hole. The coupling strength of the two modes at the centre beam hole is affected by the size of the beam hole, which is not conducive to the design and optimization of the regular cell. To solve this problem, more coupling holes are added to introduce more adjustable parameters. The relationship between the position of coupling holes and the coupling strength, or group velocity precisely, has been studied and analysed in detail in [3] and shown in Fig. 5. To summarize, the increase in the longitudinal electric field or transverse magnetic field leads to an increase in the absolute value of the group velocity v_g. If the coupling hole is located in the area of a larger longitudinal electric field, the group velocity of the mode is positive, on the contrary, if the coupling hole is located in the area of the larger transverse magnetic field, the group velocity becomes negative. In the initial design, a pair of side coupling holes are added in the polarized direction of the HEM_{11} mode and at the maximum of the HEM_{11} electric field. As shown at point in Fig. 5(a)(c), the centre beam hole simultaneously couples two HEM modes and the pair of side coupling holes almost only couple the HEM_{11} mode. Specifically, the pair of side coupling holes provide stronger electric coupling to the HEM_{11} mode than the centre beam hole, so the HEM_{11} mode is a forward wave as a whole and HEM_{12} mode is a backward wave.

However, some flaws in the initial design were found out during optimization and simulation. In order to bring the group velocities of the two modes close together, namely $|V_{g1,centre}| + |V_{g1,side}| = |V_{g2}|$, the side coupling holes need to provide stronger electric coupling $|V_{g1,centre}| > |V_{g2}|$. But the aperture of the side coupling holes cannot be too large in order to avoid excessive coupling to the HEM12 mode, so the range of the group velocity of the two modes is limited. Secondly, because the HEM_{11} mode

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has both electrical and magnetic coupling, its field distribution along the central axis will have a "phase rebound" phenomenon. This phenomenon will cause certain interference to the measurement in experiments. Hence, an improved rf design of the regular cell is proposed.

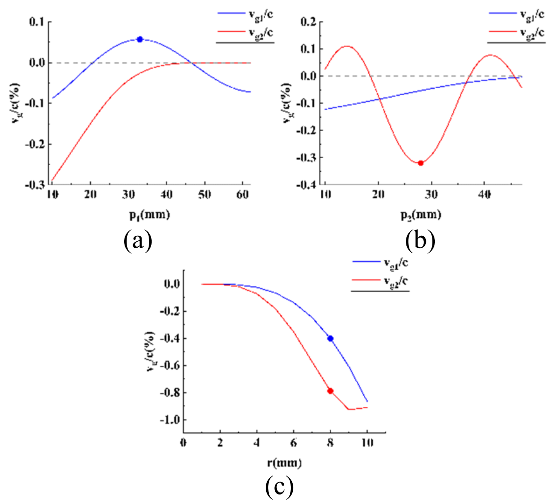

Figure 5: Group velocity of the HEM_{11} and HEM_{12} modes versus the offset distance of the side coupling hole in the vertical direction (a), in horizontal direction (b) and versus the radius of the centre coupling hole (c).

The geometric structure and parameter definition of the new design are shown in Fig. 6. The coupling holes of the two modes are selected to be opened in pairs in their respective polarized directions, and meanwhile, the radius of the centre beam hole r_1 is greatly reduced so that the two modes cut off here. As shown at point in Fig. 5(a)(b), the positions of the two pairs of coupling holes are selected at the maximum of the HEM_{11} electric field and maximum of the HEM_{12} magnetic field, so that the HEM_{11} mode is a forward wave and the HEM_{12} mode is a backward wave. In this case, the two modes are coupled from their respective side coupling holes, which is conducive to subsequent optimization and tuning work.

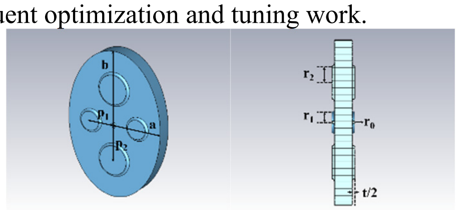

Figure 6: Geometry and parameter definition of the new regular cell.

SIMULATION RESULT

The optimization process of the new regular cell is the same as that in [3], neural network algorithm and multi-step optimization algorithm are adopted. The rf parameters is given in Table 1 compared with the initial design. It can be seen that the new design has a larger group velocity with little change in other rf parameters, which provides a larger choice range for the performance design of TTDS.

Table 1: Rf parameters of the Initial and New Design

Rf parameters	Initial design HEM11/HEM12	New design HEM11/HEM12	Unit
f_0	2.856/5.712	2.856/5.712	GHz
V_g/c	0.79/-0.81	1.69/-1.75	%
Q	9257/11785	10377/11079	
$R_\perp$	22.7/22.4	26.3/25.5	MΩ/m
α	0.4071/0.6296	0.1705/0.3106	

The normalized Poynting vector S'_c [5] distribution of the two modes in Fig. 7 shows that in the new design, each pair of the side coupling holes almost have the energy flow of only one mode, which means the coupling of the two modes is successfully separated. In addition, although Sc has not been studied specifically, the synthetic deflection field shows the potential to reduce maximum Poynting vector S_{c_max}. Further studies will be carried out in the future.

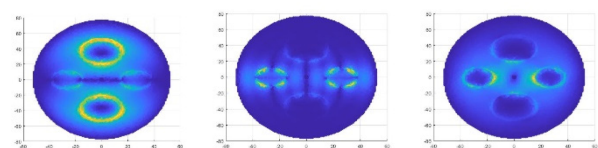

Figure 7: S'_c distribution of the HEM_{11} mode (left), HEM_{12} mode(middle), and their combine field(right).

CONCLUSION

To meet new requirements from proton FLASH therapy and advanced beam diagnostics, the new design of the TTDS has been proposed to provide a variably polarized deflecting field at SSRF/SXFEL. The TTDS is a dual-mode structure and its 15-cell prototype has been designed and fabricated at SSRF/SXFEL. Driven by two different power sources, it can work on both the HEM11 and HEM12 modes in vertical and horizontal deflecting directions simultaneously. In the processing of optimization and measurement, some limitations of the initial design were exposed. SSRF/SXFEL has proposed a new rf design of the regular cell to improve the rf performance of the TTDS. Another pair of side coupling holes are added in the polarized direction of the HEM12 mode and the centre beam hole is reduced to cut off both HEM modes.

After optimization, the new regular cell operates the two modes in their corresponding operating frequency and coupled the two modes independently in the two pairs of side coupling holes. Simulation results show that the new design have lager adjustable range of the group velocity and potential to reduce maximum Poynting vector. Further study will also be performed at SSRF/SXFEL.

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REFERENCES

[1] W.-C. Fang *et al.*, "Proton linac-based therapy facility for ultra-high dose rate (FLASH) treatment," *Nucl. Sci. Tech.*, vol. 32, no. 4, Apr. 2021. doi:10.1007/s41365-021-00872-4

[2] P. Krejcik, R. Akre, L. Bentson, and P. Emma, "A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics", in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper WPAH116, pp. 2353-2355.

[3] H. Gong *et al.*, "Design of a dual-mode transverse deflecting structure using neural network and multiobjective algorithms," *Phys. Rev. Accel. Beams*, vol. 27, no. 4, Apr. 2024. doi:10.1103/physrevaccelbeams.27.042001

[4] C.-C. Xiao, J.-Q. Zhang, J.-H. Tan, and W.-C. Fang, "Design and preliminary test of the LLRF in C band high-gradient test facility for SXFEL," *Nucl. Sci. Tech.*, vol. 31, no. 10, Oct. 2020. doi:10.1007/s41365-020-00806-6

[5] A. Grudiev, S. Calatroni, and W. Wuensch, "Erratum: New local field quantity describing the high gradient limit of accelerating structures [Phys. Rev. ST Accel. Beams12, 102001 (2009)]," Physical Review Special Topics - Accelerators and Beams, vol. 14, no. 9, Sep. 2011. doi:10.1103/physrevstab.14.099902