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DESIGN OF AN S-BAND PARALLEL-COUPLED POLARIZABLE TRANSVERSE DEFLECTING CAVITY FOR MULTI-DIMENSIONAL PHASE SPACE DIAGNOSTICS IN PHOTOINJECTORS

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Abstract

Beam quality from photoinjectors is crucial for lasing in Free Electron Laser (FEL) facilities. While phase space measurement are usually limited to 2D with conventional methods, the recently-developed transverse deflecting cavities (TDCs) with variable polarization provide the capability to measure multi-dimensional phase space information. Such information could guide the improvement of beamline setup for optimal lasing performance. We therefore propose an S-band parallel-coupled TDC, in which two chains that deflect beam horizontally and vertically are independently fed by waveguides and variable polarization can be obtained by adjusting their relative amplitude and phase. This design offers several advantages, including tunability, single-frequency operation, compactness, and high shunt impedance. In this manuscript, physical and mechanical design of this TDC as well as the planned proof-of-principle experiment will be presented in detail.

INTRODUCTION

Transverse deflecting cavity imprints time-dependent transverse kick to a charged bunch, making it an essential tool for longitudinal beam diagnostics [1]. Novel TDCs with variable kick angle (polarization) can be further utilized for multi-dimensional phase space measurements as well as rapid scanning in proton therapy. Recently, several types of polarizable TDC have been developed with advanced technologies, such as fully axial-symmetric cells with E-rotator [2, 3], dual-mode dual-frequency cells [4, 5], and alternating cells with orthogonal TE°_{11}-like modes by individual feeding [6].

Based on the parallel-coupled technique applied in high gradient accelerating structures [7, 8], we have proposed a new type of polarizable TDC with two alternating but isolated chains, each containing parallel-fed cells that support horizontally or vertically polarized TM°_{11}-like mode [9]. Variable polarization is achieved by adjusting the amplitude and phase of the input power to the chains. Our design presents the following advantages: 1) the asymmetric cells can be tuned after brazing, which relaxes the machining tolerance; 2) the structure uses a single power source; 3) only two input ports are needed for the entire structure, which simplifies the waveguide network; 4) the cells operating in π-mode have high shunt impedance. This parallel-coupled polarizable TDC is intended for use at the end of the photoinjector of the planned Shenzhen Superconducting Soft X-Ray Free-Electron Laser (S^3FEL) [10].

In our recent study, we have improved our initial design so as to simplify the parallel-feeding waveguide and enhance fabrication feasibility. The physical and mechanical design of two prototype structures have been completed. The 8-cell prototype will be utilized to demonstrate the fabrication and tuning technologies, while the 16-cell prototype will undergo beam testing in the proof-of-principle experiment at Dalian Coherent Light Source (DCLS) [11].

INITIAL STRUCTURE DESIGN

In the initial design (Fig.1), the deflecting cells are racetrack-shaped to ensure large degenerate mode separation, supporting the desired polarization while minimizing coupling between neighboring cells [9]. The π-mode cells are individually fed by the parallel-coupled waveguide under critical coupling conditions. Corrugations are included in the waveguide to slow the phase speed v_p to match the speed of light c, satisfying the synchronization condition. It should be noted that the phase advance of the corrugation (denoted as θ) should be lower than π to propagate the input power and uniformly distribute it into the deflecting cells. θ is set to $2\pi/3$ in the initial design.

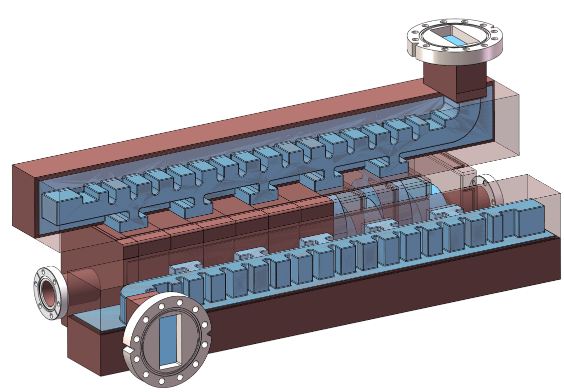

Figure 1: Schematic layout of the initial design.

In parallel-coupled accelerating structures, the cavity is usually machined as two halves to reduce fabrication costs and complexity [7, 8]. Due to the transverse surface cur-

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rent on the iris in the TM°_{11}-like deflecting mode, however, the quality factor could be largely reduced if the structure is machined into two halves or quadripartite pieces in the proposed TDC design. The cells is therefore designed to be milled individually. Meanwhile, the feeding waveguide has to be machined separately since it contains 1.5 corrugations per deflecting cell. This configuration presents challenges when brazing the cells and waveguides, especially for long structures.

UPDATED STRUCTURE DESIGN

To address the challenges in the initial design, an updated structure has been developed as illustrated in Fig.2. The physical and mechanical design is presented in this section. The RF properties of the structure is simulated by the frequency domain solver of CST Microwave Studio [12].

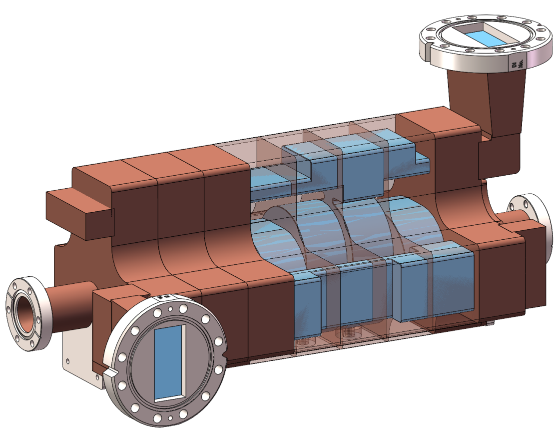

Figure 2: Schematic layout of the updated design (the shorter prototype structure).

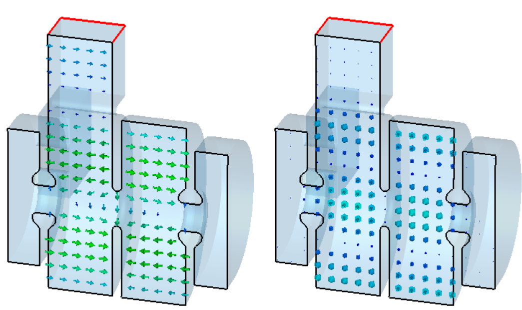

Figure 3: The E-field (left) and the H-field (right) distribution of the two-cell unit.

In contrast to the initial design which utilized alternating single cells, the updated design features alternating units with two coupled cells placed orthogonally along the structure. Since the cells still operate in π-mode, such configuration leads to the synchronized condition in the parallel-coupled waveguide to be $v_p = 2c$. As a result, the corrugations in the waveguide can be simplified, and the waveguide can be milled together with the deflecting cell into one piece. These pieces can then be brazed in a manner similar to regular accelerating cells, a process that is feasible even for longer structures.

The deflecting cells retain the racetrack shape from the initial design. Two coupled cells with the same polarization form an unit that is connected to the parallel-feeding waveguide through a slot under critical coupling conditions. The unit is designed with large aperture between the two cells to provide adequate frequency separation between 0-mode and π-mode. Meanwhile, nose-cone is set between units to reduce their inner coupling. The field distribution of a two-cell unit is illustrated in Fig 3.

Two prototypes, a shorter one (#1) with 8 cells for machining and tuning demonstrations, and a longer one (#2) with 16 cells for high power test and beam diagnostics, have been developed. The key parameters of their two-cell unit are summarized in Table 1.

Table 1: Parameters of the two-cell unit in the prototype structures

Parameter	**Prototype #1**	**Prototype #2**
Iris thickness	6 mm	
Beam aperture diameter	20 mm	
Cell length	50.01 mm	52.48 mm
Frequency	2997.22 MHz	2856.00 MHz
$0/\pi$ modes separation	28.50 MHz	22.68 MHz
Degenerate separation	502.95 MHz	425.00 MHz
Quality factor	18459	19214
R_{tran}*	28.68 MΩ/m	27.34 MΩ/m

* Effective transverse shunt impedance

The parallel-feeding waveguide is designed following the methodology introduced in Ref. [7,8]. Each T-junction comprises a smooth waveguide section to satisfy the synchronized condition $v_p = 2c$, a bump to meet the power dividing ratio requirement, and another waveguide connecting to the corresponding two-cell unit. As the design procedures for both prototypes are similar, the following detailed results mainly focus on Prototype #1.

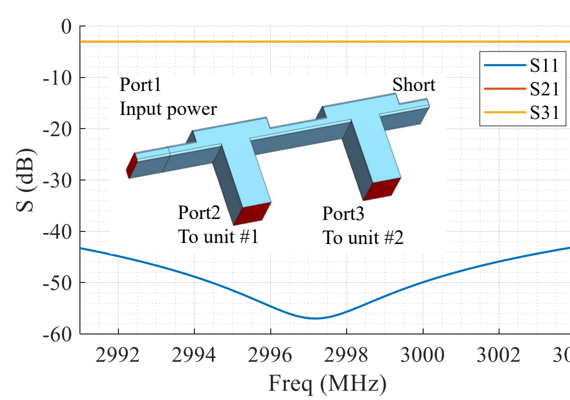

Figure 4: One parallel-feeding waveguide and its S-parameters.

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The S-parameters of one parallel-feeding waveguide are illustrated in Fig. 4, which demonstrates the input power in divided into two units with negligible reflection.

The S-parameters of the full assembled structure with four two-cells units and two waveguides are illustrated in Fig. 5. Since the inner coupling between cells is weak due to large degenerate mode separation and nose-cone setup, the units resonate at their respective *pi*-mode frequency and the two chains are well isolated from each other.

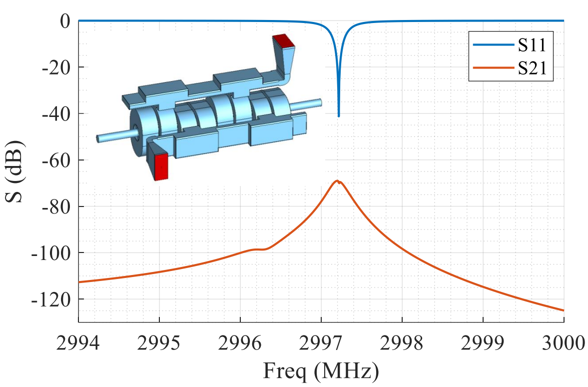

Figure 5: The fully assembly and its S-parameters.

The on-axis field distribution is illustrated in Fig. 6. Only one chain is excited by the corresponding input waveguide and field balance above 95% is obtained by slightly tuning the end cells.

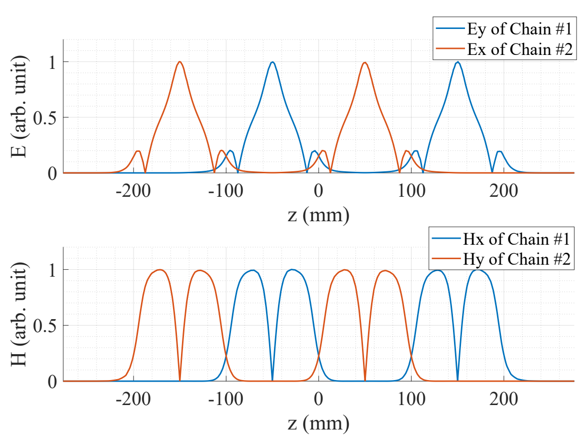

Figure 6: On-axis E-field (top) and H-field (bottom) distribution of the structure when fed by individual waveguide ports.

Key parameters of the updated TDC structures are summarized in Table 2.

TRANSIENT ANALYSIS

The cells in the proposed parallel-coupled polarizable TDC operate in standing-wave mode, which needs relatively long filling time to reach steady status. When driven by 4 μs klystron, as will be applied in photoinjector of S^3FEL, the

Table 2: Parameters of the updated TDC structures

Parameter	Prototype #1	Prototype #2
Number of cells	4+4	8+8
Total cell length	400.08 mm	839.68 mm
Full structure length	554 mm	1040 mm
Total Input power	5.00 MW	15.00 MW
Deflection voltage*	5.36 MV	13.12 MV

* Steady status with long input pulse

RF field in Prototype #1 will not reach the steady status, as illustrated in Fig. 7.

One potential solution is to generate RF pulses with higher magnitude at the start and lower magnitude towards the end via the low-level RF system. By adjusting the magnitude ratio, a flat-top could be obtained even with short RF pulses.

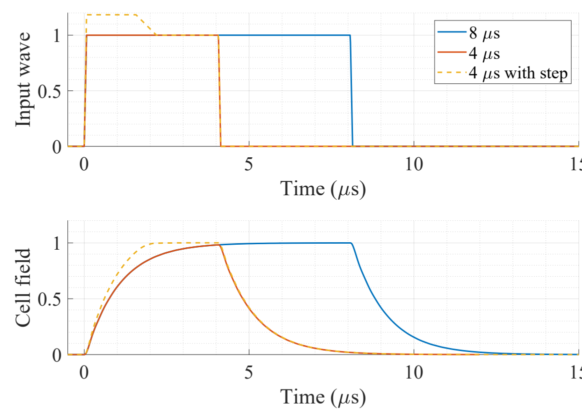

Figure 7: Normalized magnitude of input power (top) and RF field inside cells (bottom).

PLANNED PROOF-OF-PRINCIPLE EXPERIMENT

The proof-of-principle experiment is scheduled to be conducted in DCLS where low-emittance electron beam is produced by an S-band 1.6-cell photocathode RF gun and accelerated to 300 MeV via six S-band 3 m-long linacs [11].

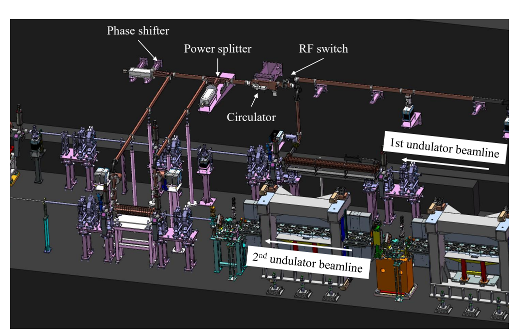

Figure 8: Schematic layout of the proof-of-principle experiment.

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Prototype #2 will be installed at the end of the second undulator beamline, as illustrated in Fig. 8. The structure will be driven by a 45 MW klystron that routinely powers a 2 m-long traveling-wave TDC with fixed polarization on the first undulator beamline. Accessorial waveguide network includes an RF switch, a variable power splitter to adjust the ratio of input power into the two chains, a phase shifter to fine-tune the relative phase of the two chains, a circulator to protect the klystron from the reflection power during RF rising and falling edges, directional couplers, and RF windows.

In the proof-of-principle experiment, Prototype #2 will be high power tested and utilized for reconstruction of 3D charge-density distribution [13].

CONCLUSION

An S-band parallel-coupled TDC has been proposed for multi-dimensional phase space diagnostics in photoinjectors. The structure consists of two chains that deflect beam horizontally and vertically, where variable polarization can be obtained by adjusting the relative amplitude and phase of the input power to the chains. The physical and mechanical design of two prototypes have been completed and the structures are currently under development. The proof-of-principle experiment is scheduled at DCLS in 2025.

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