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DESIGN OF X-BAND DISTRIBUTED-COUPLING ACCELERATING STRUCTURE

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Abstract

Distributed-coupling structures has been proposed as an advanced type of high-gradient accelerators, RF power flow independently into each cavity.This method has few advantages such as high shunt impedance, superior power efficiency, and low costs. And the most distributed-coupling structures typically set 0° or 180° as the phase advance which was proved to be a precondition for providing an equal amount of power to each cell.In this study we proposed a new method of distributed-coupling accelerating with phase advance greater than 180°. Based on the analysis of microwave network, phase advance of 210° was designed and simulated. These structures include couple of parallel waveguides loaded by accelerating cavities, by means of changing parameters of every single T-junction to meet power requirement. This choice of angle will significantly reduce costs without affecting the shunt impedance.

INTRODUCTION

In conventional acceleration structures, microwave power is coupled along cavities through the beam pipe, which increases the probability of breakdown during high-power tests, thus limiting the shunt impedance and accelerating gradient. Consequently, the distributed-coupling acceleration structure has been proposed. Unlike conventional high accelerating gradient structures, RF power is fed independently to each cavity through external waveguides, with virtually no power flow through the cavities axially. This feature helps reducing the breakdown rates and optimizing the cavity shape to minimize the surface heating. It is known that the phase velocity of microwaves in smooth waveguides exceeds the speed of light, making it necessary to design the appropriate cavity position to assure the right phase. In past few years, SLAC have developed the first X-band high gradient distributed-coupling accelerating structure [1], where the phase velocity in the waveguide is twice the speed of light, including interleaving pairs of cavities of two structures of pi/2 phase advance to obtain greater accelerating distance.

Subsequently, Jiang at Tsinghua University used microwave network theory to demonstrate that a power distribution network with multiple identical T-junctions can achieve equal power injection if the phase advance is 0 or 180°. They designed a parallel feed accelerating structure using corrugated waveguides as slow-wave structures, with a phase advance of 180° between cavities [2]. This configuration where the phase velocity in the waveguide is equal to the speed of light ensures the beam undergo the correct phase, making the accelerating structure more compact. Regarding small beam iris, phase advance of 180° between cavities is not the most optimal choice in terms of shunt impedance. Therefore, SLAC later developed distributed-coupling structures with 3/4 pi [3] and 2/3 pi phase advance [4], which involve couples of 180° phase advance structure with power in different phase injecting respectively and spatially combining cavities from different structures. On one hand, these methods increase the complexity and cost of accelerating system; on the other hand, they impose strict demands on manufacturing capabilities.

In this paper, we propose a new distributed-coupling traveling-wave accelerating structure with a phase advance of 210°. With the same length, the number of cavities is effectively reduced if a larger phase advance between cavities is chosen, significantly lowering costs. Calculations show that the shunt impedance of 210° compared to 180° does not reduce too much, which validates the significance of continuing this work. For the convenience of manufacturing, we use smooth rectangular waveguides and optimize the size of the T-junction nodes to meet the requirements for equal power distribution. The direction of microwave power flowing is opposite to that of beam transmission, while adjusting the long edge of the waveguide can change the phase velocity to ensure beams in accelerating phase.

ANALYSIS OF MICROWAVE NETWORK

The schematic drawing of the microwave network of Three-ports distributed-coupling structure is shown in Fig. 1, where the power is injected to port 1, flows into the accelerating cells through three branches, and then out of port 5. It is necessary to assume that power is divided into several equal parts in order to ensure the same electric field amplitude in each accelerating cavity. In order to analyze the division network of N ports, the general expression is first derived from the simplified structure of three ports. We can write the scattering matrix M_s for the network in Fig. 1:

$$M_s = \begin{bmatrix} a & b & be^{j\theta} & be^{j2\theta} & k \\ b & c & d & de^{j\theta} & b \\ be^{j\theta} & d & ce^{j2\theta} & de^{j2\theta} & be^{j\theta} \\ be^{j2\theta} & de^{j\theta} & de^{j2\theta} & ce^{j4\theta} & be^{j2\theta} \\ k & b & be^{j\theta} & be^{j2\theta} & a \end{bmatrix} \quad (1)$$

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The lowercase letters represent the reflection or transmission coefficients for each port, and the phase of RF power in each cell must be required as shown in Eq. (1), otherwise θ is not allowed to be the arbitrary angle. If the power parallel- coupled structure exists, the ideal power transmission is reciprocal and lossless. The constraint holds when θ is 0 or 180° [2], and Eq. (1) also holds when θ is an arbitrary angle after calculation. Thus, this expression form of scattering matrix can be extended to N-ports structure, which proves that the distributed-coupling structure with arbitrary phase advance is theoretically working.

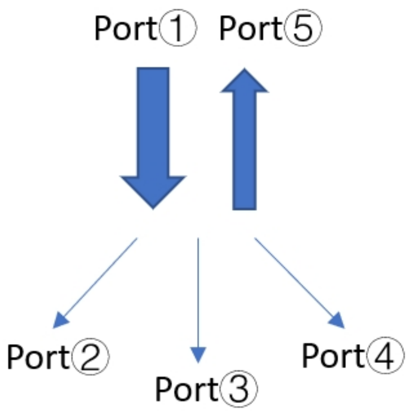

Figure 1: RF power flows from port 1 to port 5 and is equally distributed to the three ports (2, 3, 4); the three divided power flow is equal in absolute value and differ in phase by θ ; assuming that the magnitude of the absolute value of the incident power is 1.

WAVEGUIDE STRUCTURE OF POWER DIVIDER

Conventional distributed-coupling structures can be split into multiple identical T-junctions, and the distance between each T-structure necessarily equals to one or half of the wavelength in the waveguide, which represent a phase advance of 0 or 180°. Parallel-coupled structures with arbitrary phase shift requires not only changing the distance between T-junctions to the length corresponding to the designed phase advance, but also redesigning the physical structure of T-junctions to ensure equal power division. We designed the structure using WR90 rectangular waveguide and the phase shift is set to 150°, and the physical structure of the three-port parallel-coupling is demonstrated in Fig. 2.

$$M_{150} = \begin{bmatrix} -11.8 & -10.7 & -10.6 & -9.9 & -1.8 \\ -10.7 & -1 & -9.9 & -10.6 & -10.7 \\ -10.6 & -9.9 & -1 & -19 & -19 \\ -9.9 & -10.6 & -19 & -1 & -19 \\ -1.8 & -10.7 & -19 & -19 & -11.8 \end{bmatrix} \quad (2)$$

As can be seen from the figure, on the basis of the original T-junction structure, we changed the dimensions of the interface between the main waveguide and the branch waveguide filleting the edge in radius of 0.5 mm. The power is

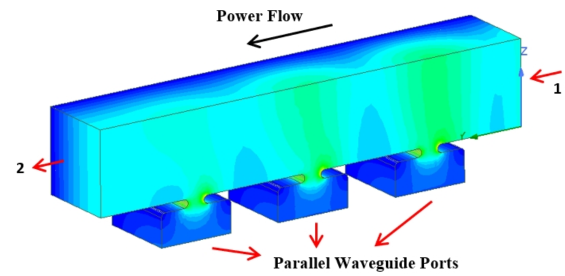

Figure 2: Half physical structure design in HFSS: 1-RF input power; 2-RF output power. Colormap shows complex E-field distribution in structure and calculation was operated at 11.424 GHz.

divided equally in amplitude and output from three parallel waveguide ports into the accelerating cell, and the distance between the axes of the three ports is $(150/360) \cdot \lambda_g$, where λ_g is the wavelength in the waveguide, with a phase shift of 150°. The corresponding scattering matrix of structure is shown as Eq. (2), which is the same with Eq. (1) formally.

DESIGN OF DISTRIBUTED-COUPLING ACCELERATING STRUCTURE

The phase advance of the external power flow in the neighboring T-junction is 150°. Since the wavelength in the waveguide is larger than that in the vacuum, the length of the T-junction is larger than the length of the corresponding accelerating cell, resulting in a waste of space. We proposed the structure shown in Fig. 3, where the power flow direction is opposite to the beam transmission direction and the phase advance of cell is 210°. The phase velocity is optimized by changing the broadwall waveguide to meet the equation: $150/360\lambda_g = 210/360\lambda_a$, where λ_a is the wavelength in vacuum and λ_g is the wavelength in the waveguide.

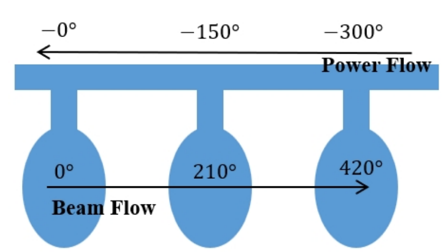

Figure 3: Simple schematic of the accelerating structure, power flow and beam flow are in opposite directions. The phase velocity is optimized by changing the broadwall waveguide dimension.

We simulated the accelerating quarter-cell accelerating structure (as seen in Fig. 4) in HFSS with the Master-Slave boundary angle set to 210° and an operating frequency of 11.424 GHz. The geometry of the accelerating cell was optimized to obtain higher shunt impedance. Table 1 demonstrates the main parameters of the accelerated structure compared to the $2\pi/3$ mode and π mode.

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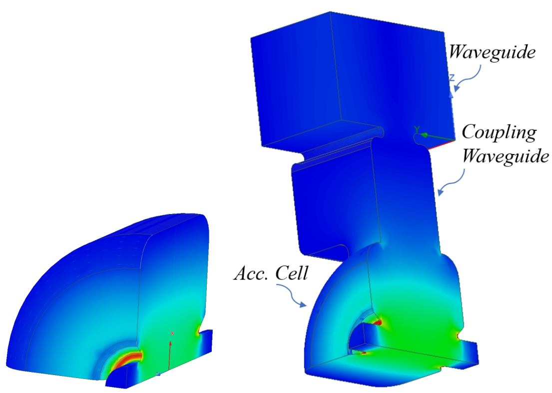
Table 1: Comparison Between Distributed-Coupling Accelerating Structure with 210°, 120°, and 180° Phase Advance

Parameter	**210 deg**	**120 deg**	**180 deg**
Cell Length [mm]	15.31	8.75	13.12
Phase Advance [deg]	210	120	180
Aperture Radius [mm]	1.5	1.5	1.5
Q-value	9348	6208	8561
Shunt Impedance [MOhm/m]	139	132	157
Accelerating Gradient [MV/m]	100	100	100
Peak E-Field [MV/m]	261	380	280



(a) (b)

Figure 4: (a) Quarter-cell HFSS model with phase advance of 210° and electric field profile plot, (b) the single T-junction with quarter-cell design and electric field profile. Simulation are operated in the HFSS eigenmode.

We also designed a 3-cell accelerating structure working in 210° mode and 11.424 GHz, shown in Fig. 5. The structure was composed by three T-structure shown in Fig. 4b, where the dimension of every junction window was designed respectively to ensure equal amplitude of accelerating E-field.

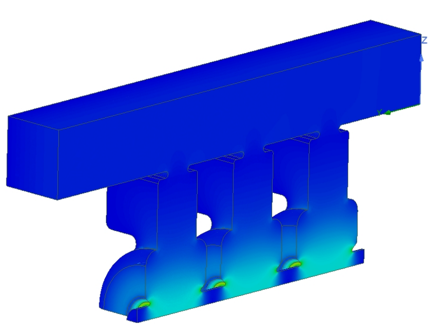
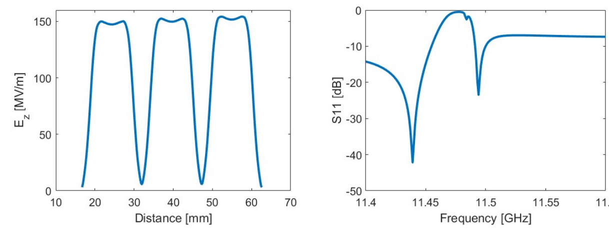


Figure 5: Three-cells distributed-coupling accelerating structure and E-field profile plot.

The accelerating gradient over the cells retains an even distribution, and the calculated field distribution and S11 parameter are shown in Fig. 6. In a wide frequency range, the structure features a single resonance frequency, which demonstrates a good frequency domain property.



(a) (b)

Figure 6: (a) E_z field distribution on the axis and (b) the S11 parameter of distributed-coupling structure in cold test.

CONCLUSION

In summary, we designed a new type of distributed-coupling structure with phase advance of 210°, which differ from conventional these structures. The direction of RF power flow is opposite to the beam to avoid waste of space with phase matching. In simulation, the 210° mode shows considerable shunt impedance and Q-value comparing to $2/3\pi$ mode and π mode. Consequently, this special design helps reducing costs, and will fabricated and tested in the near future.

REFERENCES

[1] S. Tantawi, M. Nasr, Z. Li, C. Limborg, and P. Borchard, "Design and demonstration of a distributed-coupling linear accelerator structure," Phys. Rev. Accel. Beams, vol. 23, no. 9, p. 092001, Sep. 2020, `doi:10.1103/PhysRevAccelBeams.23.092001`.

[2] Y. Jiang, J. Shi, H. Zha, J. Liu, X. Lin, and H. Chen, "Analysis and design of parallel-coupled high-gradient structure for ultrashort input power pulses," Phys. Rev. Accel. Beams, vol. 24, no. 11, p. 112002, Nov. 2021, `doi:10.1103/PhysRevAccelBeams.24.112002`.

[3] J. B. Rosenzweig *et al.*, "A High-Flux Compact X-ray Free-Electron Laser for Next-Generation Chip Metrology Needs," Instruments, vol. 8, no. 1, p. 19, Mar. 2024, `doi:10.3390/instruments8010019`.

[4] S. Antipov, V. Dolgashev, R. Kostin, and S. Kuzikov, "High Shunt Impedance Accelerating Structure with Distributed Microwave Coupling," Proceedings of the 9th Int. Particle Accelerator Conf., vol. IPAC2018, p. 3 pages, 0.793 MB, 2018, `doi:10.18429/JACOW-IPAC2018-WEPMF069`.