DEVELOPMENT OF A PROTOTYPE VARIABLE POWER DIVIDER FOR THE ILC POWER DISTRIBUTION SYSTEM *

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Abstract

The R&D of the radio frequency (RF) power distribution system (PDS) for the International Linear Collider is ongoing. In every RF station, the PDS is necessary to drive 39 superconducting RF (SRF) cavities with the RF power provided by a 10 MW multibeam klystron. To maximize the beam energy, PDS uses power dividers and phase shifters, which allow driving all cavities just below their respective operational limits during the flattop. As a necessary element of the PDS, a variable power divider (VPD) was developed. A prototype was constructed by assembling two folded magic tees (FMTs), four H corners, and two variable phase shifters (VPSs).

INTRODUCTION

The International Linear Collider (ILC) is a future linear electron-positron collider with a center-of-mass energy of 250 GeV [1, 2]. In the main linacs, approximately 8,000 nine-cell TESLA-type superconducting RF (SRF) cavities are driven in around 200 RF stations. These cavities will be operated at 1.3 GHz using pulsed RF power with a pulse width of 1.65 ms at a repetition rate of 5 Hz. The ILC uses SRF cavities with an average accelerating gradient of 31.5 MV/m, with a spread of ±20%.

In an RF station, one klystron drives 39 SRF cavities via a waveguide system called the power distribution system (PDS) as shown in Fig. 1. The RF power from a klystron is distributed into three waveguide systems, called local power distribution systems (LPDSs). Each LPDS consists of three sub-local power distribution systems (sub-LPDSs). There are 13 cavities in each LPDS, and 4 or 5 cavities in each sub-LPDS. The remotely controlled variable power dividers (VPDs) are used to distribute the necessary RF power at the required phase to each sub-LPDS, and variable hybrids are used to deliver the required power to each cavity [1]. To operate each cavity at its maximal gradients, the coupling ratios of the variable hybrids are adjustable by ±25% from their average value [3].

The klystron emits up to 10 MW RF power in total via two ports, which are distributed into three LPDSs using variable hybrids. The variable hybrids have limitations, such as output phase variation on changing the coupling ratio, lack of phase adjustment capability, and comparatively low power operation due to an unpressurized design. The use of 5 MW VPDs is proposed instead of the variable hybrid to overcome the limitations [4].

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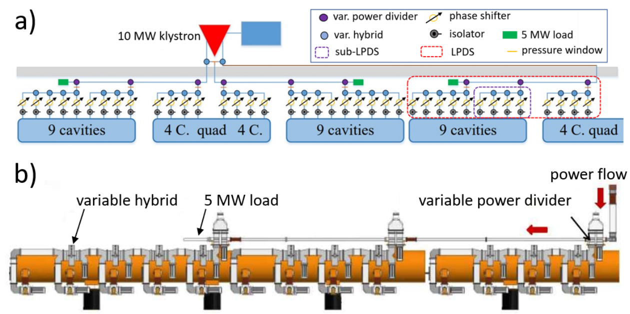

Figure 1: (a) Power distribution system for the ILC. (b) Local power distribution system for the ILC [1].

Following the design of the VPD developed at SLAC as shown in Fig. 2, we intend to combine power dividing and phase-shifting capabilities in a single device [5]. The VPDs developed at SLAC are operated at a pulsed power of 3.2 MW with a pulsed length of 1.60 ms. The output power ratio between port-2 and port-3 can be freely adjusted, and the output phase can be shifted by up to 120 degrees. The U-bend phase shifters uses finger stock to slide inside the spacer with electric contact. The use of finger stock can lose contact, and the probability of arcing is increased [6]. To avoid this, for the prototype VPD, the U-bend phase shifter is replaced by a variable phase shifter and spacers of various lengths. For the ILC, the operational limit is to be increased up to 5 MW. The output phase needs to be adjustable from 0 to 360 degrees. Therefore, the updated VPD is to be developed to meet the ILC requirements.

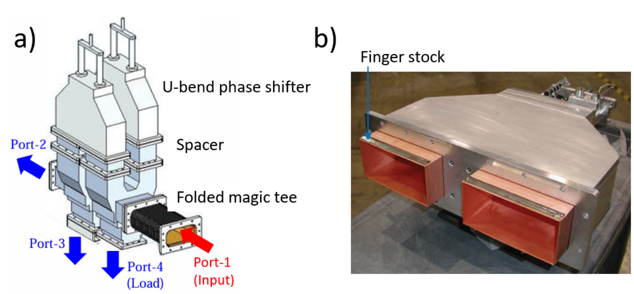

Figure 2: (a) Model of a variable power divider (VPD) developed at SLAC. (b) U-bend phase shifter used in VPD [5].

REQUIREMENTS

The VPDs are operated at 5 MW, in pulsed mode with a pulse width of 1.65 ms and a repetition rate of 5 Hz, as mentioned in Table 1. The return loss and isolated port loss are less than -25.00 dB. The electric field is less than 3 MV/m and pressurized to 0.20 MPaG by nitrogen gas to avoid the arcing [7]. The output power from port-2 (see Fig. 3) drives the cavities of an LPDS, and the output power from port-3 of two VPDs is combined to drives an LPDS. The average, minimum, and maximum power at port-2 are -1.76 dB, -2.63 dB, and -1.14 dB, respectively. To determine the output power ratio, the average cavity power is normalized to 100 units. In the minimum case, that side receives 75 units while the other receives 125 units, and vice versa. The requirements of the 5 MW VPD are summarized in Table 1.

Table 1: Requirements of a Variable Power Divider

Parameters	Value and Unit
RF power	5 MW
Operational frequency	1.3 GHz
Pulse width	1.65 ms
Repetition rate	5 Hz
N_2 gas pressure	0.20 MPaG
Electric field	< 3 MV/m
$\lvert S_{11}\rvert$, and $\lvert S_{41}\rvert$	< -25.00 dB
$\lvert S_{21}\rvert$	-2.63 to -1.14 dB
$\lvert S_{31}\rvert$	-6.37 to -3.42 dB

The 3.3 MW VPDs are used to distribute RF to the sub-LPDS. The requirements for 3.3 MW VPDs are same as the 5 MW VPD except S parameters. The RF power at port-3 is minimum -6.77 dB for the first VPD (direction from klystron to cavity) of each LPDS and maximum -0.02 dB for the last VPD of LPDS. The power at port-2 is maximum -1.03 dB for the first VPD, and the minimum power (<-30.00 dB) is dissipated in the 5 MW dummy load connected at the end of the LPDS. For 3.3 MW VPDs, the output phase at port-2 and 3 is to be adjusted from 0 to 360 degrees. The output phase is to be constant with changing the coupling ratio.

DESIGN

A prototype VPD was designed with folded magic tees, variable phase shifters, H corners, and spacers. Folded magic tees were developed as the first step toward the development of VPD [8]. They were tested in a resonant ring with 5.5 MW pulsed power, 1.65 ms pulse length, and pressurized to 0.20 MPaG using nitrogen gas. Variable phase shifters were developed for the sub-LPDS, which operate in ambient air. These phase shifters can adjust the phase by ~36 degrees. They were evaluated in a resonant ring with pulsed power of 2 MW, pulse length 2.0 ms, in ambient air.

The 200 mm by 200 mm four H corners are used to connect a folded magic tee with variable phase shifters, as shown in Fig. 3. An Ansys-HFSS model was designed for the simulations. The spacers are used on one side to adjust the output power ratio and on both sides to adjust the phase. The spacers of lengths 0 to $\lambda_g/4$ ($\lambda_g \approx 320$ mm) are employed on one side to adjust the output power ratio from 0 to 1 between port-2 and port-3. The spacers of length 0 to $\lambda_g/2$ are employed on both sides to adjust the output phase at port-2 and port-3 from 0 to 360 degrees.

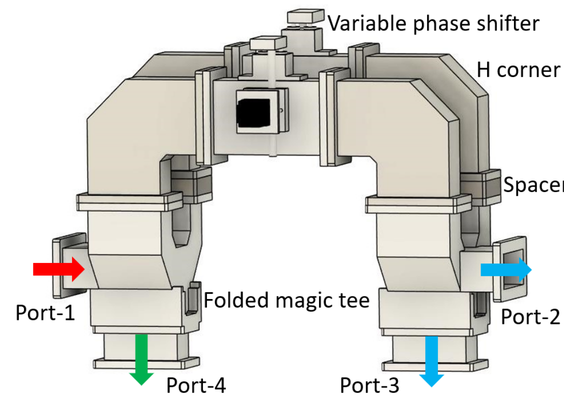

Figure 3: Model of a prototype variable power divider.

The fins of the variable phase shifters are moved in the opposite direction to adjust the coupling ratio, and are moved in the same direction to adjust the phase. The phase-adjusting capability of a variable phase shifter is allocated equally for final adjustments of both power and phase. The dimensions of the VPD are approximately 1100 mm in length, 350 mm in width, and 800 mm in height. For high-power operation, the VPDs are to be pressurized to 0.20 MPaG by nitrogen gas. As part of the VPD, the variable phase shifter will also be pressurized to the same level, requiring the development of a piston mover that can be operated in a pressurized environment.

The maximum specifications of the design of the 5 MW and 3.3 MW VPDs for the ILC are compared with the VPD developed at SLAC, as shown in Table 2.

Table 2: Comparison Between Variable Power Divider Developed (VPD) at SLAC [6] and Design for the ILC

Parameters	SLAC	Designed
RF power	3.2 MW	5 MW
Operational frequency	1.3 GHz	1.3 GHz
Pulse width	1.60 ms	1.65 ms
Repetition rate	2.5 Hz	5 Hz
N_2 gas pressure	0.12 MPaG	0.20 MPaG
S_{21} (phase)	0 to 120 deg.	Spacer±18 deg.

WORKING PRINCIPLE

The input side folded magic tee (FMT-1) splits the power equally. When there are no spacers and the fins of the variable phase shifters are at the same position, the RF input phases to both ports of FMT-2 are identical, so all the power goes to port-2. When a spacer of length $\lambda_g/4$ is added, it creates a 180-degree phase difference at the input of FMT-2. As a result, all the power is directed to port-3, as described in Equations 1 and 2.

$$V_2 = \cos\left(\frac{\phi_2 - \phi_1}{2}\right) e^{j\left(\frac{\phi_1+\phi_2}{2}\right)} \quad (1)$$

$$V_3 = \sin\left(\frac{\phi_2 - \phi_1}{2}\right) e^{j\left(\frac{\phi_1+\phi_2+\pi-\phi_x}{2}\right)} \quad (2)$$

Where, V_2 and V_3 are output voltages at port-2 and port-3 with input voltage normalized to 1. The ϕ_1 and ϕ_2 are phase shifts between two folded magic tees by two distinct pathways of propagation of the RF. The ϕ_x is a phase adjustment due to the distinct length and dimensions of port-3 side from port-2 side in VPD as shown in Fig. 3.

When the spacers of length $\lambda_g/8$ are installed on one side, the phase is delayed by 90 degrees. Due to the RF input phase difference of 90 degrees in the output side folded magic tee (FMT-2), the RF power splits equally between port-2 and port-3 as shown in Fig. 4. Then, both variable phase shifters are moved in the opposite direction to adjust the final power ratio.

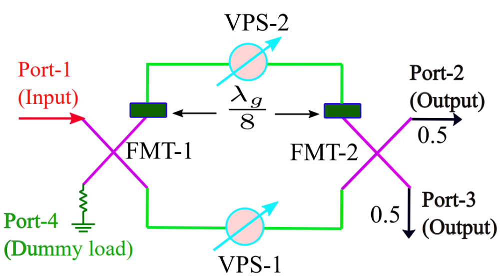

Figure 4: Schematic of the variable power divider with spacer on one side. In the sketch, FMT (folded magic tee) and VPS (variable phase shifter).

To adjust the RF output phase, spacers needs to be installed on both limbs for major adjustment as shown in Fig. 5. The spacer of length $\lambda_g/4$ on both sides shifts the output phase by 180 degrees; the additional spacer of length $\lambda_g/8$ on one side splits the power equally between the two output ports. The final adjustment of the phase (up to 18 degrees) can be completed by moving the fins of the variable phase shifters in the same direction.

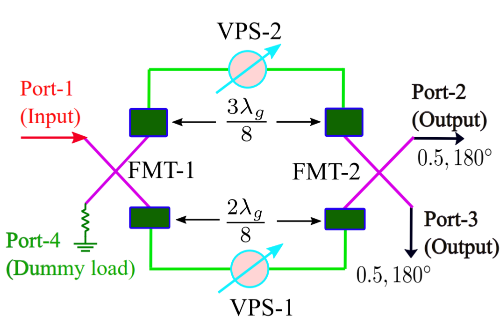

Figure 5: Schematic of the variable power divider with spacers on both sides.

SIMULATION AND LOW POWER TEST

The folded magic tees, H corners, and variable phase shifters are assembled as shown in Fig. 6. The spacers of length $\lambda_g/8$ were installed on one side to split the output power equally. Simulation was conducted in the Ansys-HFSS model by moving the fins of both variable phase shifters from 1 to 46 mm in steps of 1 mm. In low-power measurement, the coupling ratio and output phase were evaluated by using a network analyzer. For low-power measurement, the fins of the variable phase shifters were kept in the center position (16.1 mm), and then moved in the opposite direction, not by the same distance but by the same phase of 3 degrees.

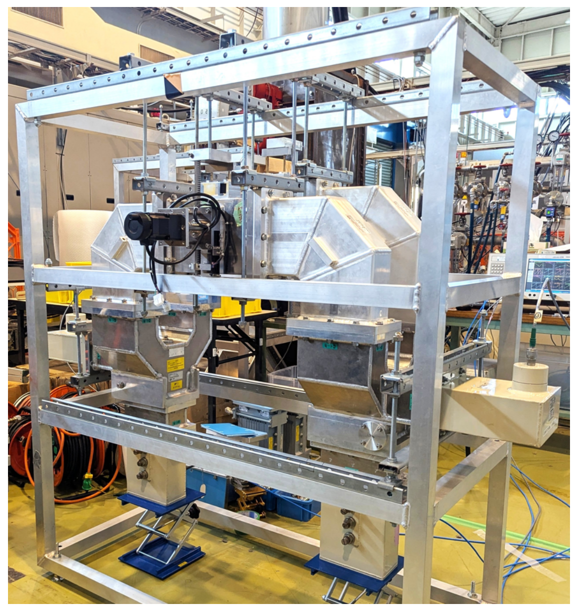

Figure 6: Photo of prototype variable power divider demonstrated at STF-KEK.

In Figs. 7 and 8, the color map is simulated, and scatter points represent the measured values. The color map in Fig. 7, shows the constant output power ratio for the same position of the fins of both variable phase shifters. The color map in Fig. 8 shows the change in the output phase by moving the fins of both variable phase shifters to the same position. The output power ratio can be changed by moving the fin of one variable phase shifter, but this method of changing output power ratio also changes the output phase, which is avoided.

The low-power measurement shows an interchanged output power ratio between port-2 and port-3 from -1.00 dB to -7.00 dB. The output phase remains constant on moving the fins of variable phase shifters in the opposite direction, as shown by the scatter plot.

Return loss $|S_{11}|$, and isolated port loss $|S_{41}|$ measured between -25.30 dB to -43.87 dB, which satisfies the requirements. The output phase at port-3 is +52 degrees from port-2. The power loss in VPD was measured to be 0.028 dB (0.64%).

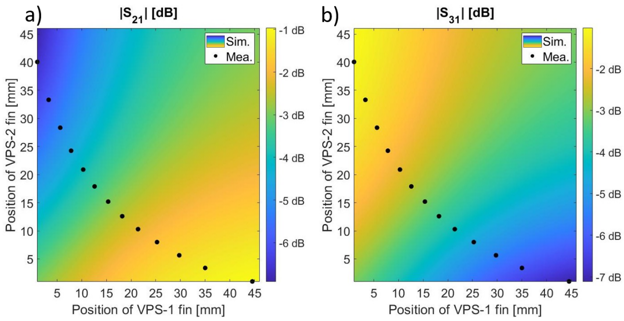

Figure 7: (a) The color map indicates simulated and scatter points measured $|S_{21}|$ dB. (b) The color map indicates simulated and scatter points measured $|S_{31}|$ dB.

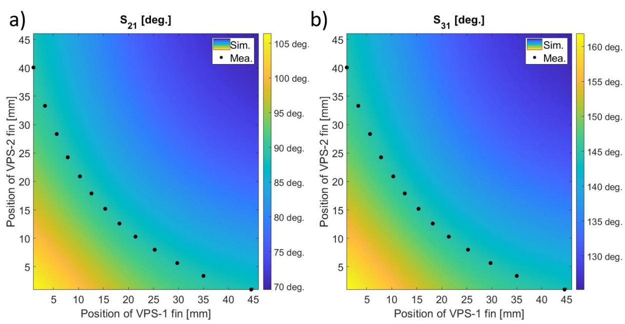

Figure 8: (a) The color map indicates simulated and scatter points measured S_{21} degrees. (b) The color map indicates simulated and scatter points measured S_{31} degrees.

CONCLUSION

A variable power divider (VPD) was developed, and a prototype was built by assembling two folded magic tees, four H corners, two variable phase shifters, and spacers. The output power ratio can be adjusted from 0 to 1, and the phase up to 360 degrees by applying spacers. After major adjustments of the coupling ratio and phase by spacers, variable phase shifters are used for the final adjustment. The VPD meets the required output power ratio range for both 5 MW and 3.3 MW systems. The return loss and isolated port loss of less than -25.00 dB satisfy the specifications. The output phase stays constant when the coupling ratio is changed.

PROSPECTS

The variable phase shifters will be updated to move the piston when pressurized. A high-power test will be conducted. In the next step, two H corners and a variable phase shifter will be integrated to form a compact U-bend phase shifter. The design of the folded magic tee will be simplified.

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