HPRF TRANSMISSION COMPONENTS STUDY AND DISTRIBUTION IN TRUMF E-LINAC

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Abstract

In September 2014, the first stage of the TRIUMF e-linac was commissioned and the high power rf systems were running in stable operation [1]. Two 300 kW klystrons, along with the key waveguide components were tested before feeding rf power into 1.3 GHz 9-cell superconducting cavities. The rf high power divider and the 360 degrees variable waveguide phase shifters were working successfully. The simulations on different waveguide structures for the power dividers, phase shifters have been studied. The comparisons of the calculation results and rf signal level tests of the both the rf components and waveguide distribution systems are presented in this paper.

INTRODUCTION

A 500 kW electron linear accelerator (e-linac) is under construction at TRIUMF. One 9-cell superconducting niobium cavity is in injection cryomodule. A 150 kW klystron will drive the cavity via two 50 kW rf couplers in phase [2]. There are two accelerating cryomodules, each housing two 9-cell superconducting niobium cavities operating at 1.3 GHz and at 2 degrees Kelvin. Another 300 kW cw klystron is employed to drive two 9-cell cavities in one cryomodule. In order to rf condition each cavity, a Variable Power Divider (VPD) is envisaged. During the rf conditioning, the power divider is set to deliver the rf power to one of the two cavities being conditioned and provide the minimum rf power to the another cavity. After rf conditioning both cavities, the VPD is set to the 3 dB position (equal power to both the cavities) for normal operation of the high power rf system to accelerate electron beams in the e-linac.

Traditionally people have employed the symmetric waveguide structure VPD to realize the operational requirements [3]. However, an asymmetric structure was considered as feasible design to meet our operation requirements. Both structures are based on the hybrids and phase shifter(s). HFSS simulations results for both structures are shown in following paragraphs. The comparisons of the calculation results help us to choose the asymmetric VPD over the symmetric VPD structure for the e-linac high power rf transmission systems. All S-parameters of the calculation and signal level rf tests are presented in this paper.

One klystron feeds rf power into the two cavities and each cavity is powered via two rf high power couplers. Therefore, at least three variable phase shifters must be installed in the waveguide distribution system to meet the operation requirements. There are three ways to reach the phase tuning requirement to operate e-linac for beam and the considerations of choosing the phase shifters in e-linac are presented in the next chapter.

300 KW VARIABLE POWER DIVIDER

This chapter gives a mechanical description for the VPD in details. General views of the symmetric and asymmetric structures of the VPD are shown in Fig. 1 and Fig. 2. TRIUMF e-linac basic operation requirements for the device are presented in Table 1.

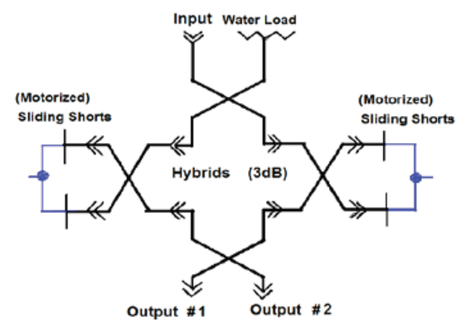

Figure 1: Symmetric waveguide structure VPD.

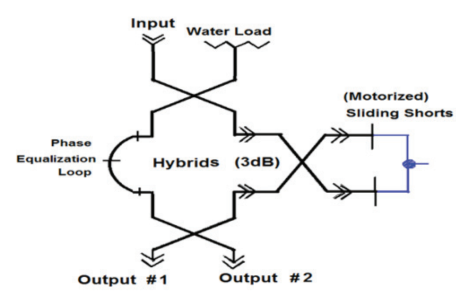

Figure 2: Asymmetric waveguide structure VPD.

Table 1: Specification of the Variable Power Divider

Frequency	[MHz]	1300 ±10
Average power	[kW]	300
Peak rf Power (full Reflected)	[kW]	>1200
Insertion Loss (maximum)	[dB]	0.3
VSWR (Max.), return loss 28.3dB		1.08 : 1
Continuously variable attenuation, with resolution better than 1.0% (0.01 dB)	[dB]	0 - 30
Operation at null position	[dB]	3 ± 0.05

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Symmetric Waveguide Structure VPD

Our initial consideration was to use the symmetric waveguide structure as shown in Fig. 1. To understand how it works and whether it would meet e-linac operation requirement, a lot of simulations have been performed. Referring to Fig. 1, two motor driving systems are used to move the slide shorts during the operations. The S-parameters of the four ports waveguide structure VPD are listed in Table 2. S11 is the input port. S21 & S41 are output ports and S31 is a port connected with 50Ω water load. Based on the simulation results, this structure can meet our requirement in the high power rf transmission system.

Table 2: Simulation Results of S-parameters in Symmetric Structure of the VPD

Position of Slide Shorts	S_{21}	S_{41}	S_{11}	S_{31}
[mm]	[dB]	[dB]	[dB]	[dB]
-43.9	-0.08	-38.68	-27.5	-30.83
0	-3.02	-3.05	-26.6	-29.79
38.6	-27.18	-0.06	-28.7	-29.51

Asymmetric Waveguide Structure VPD

As shown in Fig.2, the asymmetric waveguide structure VPD is more compact. The questions are "If the rf performance can meet the e-linac operation requirement? What are the lengths for the equalization loops?" Theoretically, there are three loop lengths to meet the operation requirements. Suppose that the hybrid coupling were 3.0 dB, the rf power entering the input of hybrid is split equally resulting in two signals with equal amplitude but quadrature phase. One of the outputs is fed into the output 3 dB hybrid thru the equalization phase loop while the other is routed through a variable phase shifter. The phase equalization loop length is set the same insertion phase length as the phase shifter settings. If the phase shifter is set such that the phase length for both paths between the input and output hybrids are the same, the signals arrive at the output hybrid with the same relative phase as they left the input hybrid. As a result, the two signals will re-combine and 100% of the input power will exit the output port 1. By changing the phase relationship of two signals arriving at the output hybrid, the output power level is split between output port 1 and 2. This can be done by adjusting the phase shifter and the output power level is varied. A phase shifter of 180^0 causes the signals arriving at the output hybrid to be in reverse quadrature. As a result the signals re-combine in the output hybrid to produce 100% rf power at output port 2. By varying the phases of the phase shifter between zero to 180 degrees the output rf power varies between zero to 100% of the input power.

The simulations of waveguide structure based on 3 dB hybrids at 1300 MHz have been performed using HFSS. A fixed equalization loop length is set. The results of the simulation show that models of the hybrid are very critical. The detailed optimizations of the hybrids and slide shorts in the device have been performed with success. As discussed previously, the unequal split of the rf power to the two output ports will result in both amplitude and phase differences. The output couplings, matching, and isolations among the four ports are becoming so difficult that you could not achieve the technical requirement. It should work well if the coupling is better than 3.0 ± 0.02 dB. The VPD will work at any output power levels in the two output ports if the positions of the slide shorts could be moved within 0.05 mm accuracy. Fig. 3 shows the couplings of two output ports with the position of slide shorts in the variable phase shifter. The typical values of the cavities rf conditioning and operational modes are shown in Table 3.

The phase differences between two output ports and a ratio of the reflected rf power from cavities to water load connected with the VPD and back to the input rf source have been studied in all operational scenarios in the simulations as well.

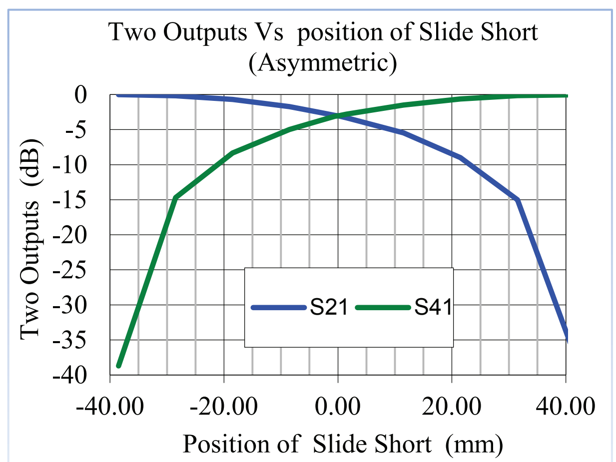

Figure 3: Power division at two output ports in asymmetric structure of the VPD.

Table 3: Typical Operation S-parameters in Asymmetric Structure of the VPD

Position of Slide Shorts	S_{21}	S_{41}	S_{11}	S_{31}
[mm]	[dB]	[dB]	[dB]	[dB]
-38.5	-0.01	-38.7	-37.5	-34.89
0	-3.02	-3.02	-29.2	-31.95
41.5	-37.04	-0.03	-29.71	-35.51

RF Signal Level Measurements of the VPD

We are clear that both symmetric and asymmetric structure of the variable power dividers satisfy the rf operational requirements for TRIUMF e-linac after simulation and study. However the asymmetric structure occupies less space, has one remote control system, and is less expensive compare to the symmetric structure which has two remote controlled phase shifters. An asymmetric waveguide structure VPD was determined to be adopted for the e-linac rf high power transmission system.

RF signal level measurements of the VPD on the test-bench have been verified and the results demonstrated excellent S-parameters for all ports have been achieved. Fig. 4 and Table 4 present the rf performance of the two output ports. Swapping the rf input port 1 and water load port with two output ports, one can get the similar S-parameters as shown here. The VSWR of the VPD is better than 1.07 in all operation ranges and the insertion loss is less than 0.30 dB (0.17 dB).

The phase relations of the VPD between two output ports are shown in Fig. 5. The phase differences are very small between two output ports. However there is a variable phase shifter utilized downstream of the VPD to compensate any phase adjustments between the two cavities powered by one klystron.

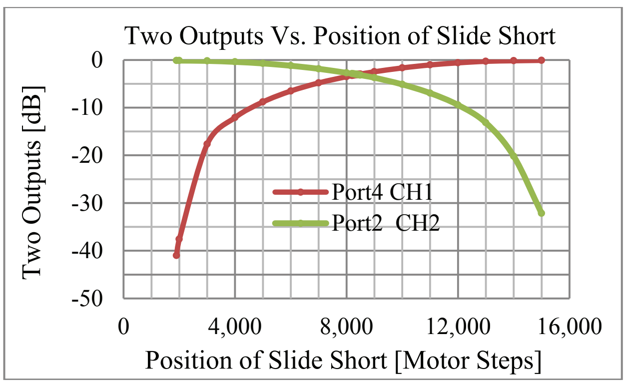

Figure 4: RF signal level measurements of the VPD.

Table 4: Typical Power Division Values of the VPD Measured at RF Signal Level

S-parameters vs. Positions of the Slide Short

Position of Slide Shorts [motor steps]	S_{21} [dB]	S_{41} [dB]
1900	-0.132	-41.02
8400	-3.08	-3.07
15000	-32.18	-0.092

Remote Operation of the VPD

The first prototype VPD was shipped to TRIUMF and verified on test-bench at rf signal level before installing in the system. The VSWR in operation mode, i.e. divided rf power equally for two cavities is about 1.02 and the VSWR is not higher than 1.055 when rf power feeding into either one of the two cavities. The insertion loss is less than 0.2 dB, which is better than our specification of not more than 0.4 dB. The resolution of rf power deviations is ± 0.01 dB by means of the MAX-410 step motor controller. The measurement results agree with the simulations and meet the e-linac operation requirements [4]. The similar results have been achieved when the rf input ports are interchanged.

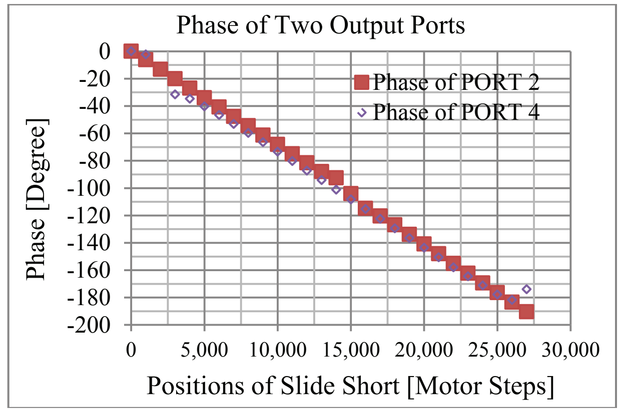

Figure 5: RF signal level measurements of the VPD.

PHASE SHIFTERS

As described previously, we utilize one 300 kW klystron to feed into two superconducting RF cavities. Each cavity is coupled with rf power via two 50 kW rf power couplers in phase. For the same cavity, the waveguide lengths in the two paths from VPD to the two rf power couplers are quite different. We intended to fix one leg length and change the length of another leg to balance the phase difference between two power couplers. There are a few options available:

1. In e-linac waveguide layout system, there are ‘M’ type paths for each leg. We can balance the phase difference by adding some waveguide pieces at the two sides of ‘M’ section. It can realize the phase balance at rf signal level. But we do not know if it works when at high power without tuning phase.
2. There are small waveguide section phase shifters with two stubs available in the market. The range of variable phase is not more than 50 degrees. Based on item one above, using a two stubs phase shifter can meet our phase balance requirement. In this case the range of phase adjustment will be about ± 25 degrees when at high rf powers.
3. There are three stubs matching waveguide tuner with phase variable (about 80 degrees) function in the market. However the return loss of the device is so poor, not better than 25 dB and it requires two motor control systems in operation.
4. Variable 360 degree hybrid phase shifter will meet our requirement but the size of it is very large. In the e-linac, one klystron there is three variable phase shifters for the phase balance between couplers and cavities. A detail layout of the waveguide distribution and

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support system is a challenge due to the limited space in klystron room and e-linac hall.

RF Signal Level Tests of the Variable Phase Shifters

After many discussions with vendors, we selected the variable 360 degrees hybrid WR650 waveguide phase shifters for the high power rf transmission lines in the e-linac system [5]. The dimension of the phase shifter is approximately 2 m x 1.7 m x 0.5 m. So we have to design the waveguides distribution and supports in good manner as the limited space.

In e-linac phase one, four waveguide 360 degree phase shifters have been purchased. The rf signal level tests have been performed on the test-bench at TRIUMF. The variable phase range is over 360 degrees. They are of a very good linearity for phase shift and motor steps. One degree phase changing equal to 72 steps of motor moving, the resolution is better than 0.1 degree, which is higher than our specification. The rf insertion loss is about 0.1 dB. The VSWR is between 1.01 to 1.06 for all modes of operation. Detail performs of the phase shifter are presented in following Fig. 6 – Fig. 8 and Table 5.

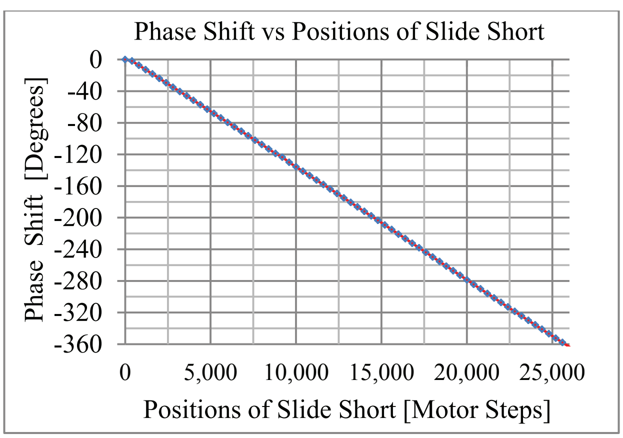

Figure 6: Phase variable range of the phase shifter.

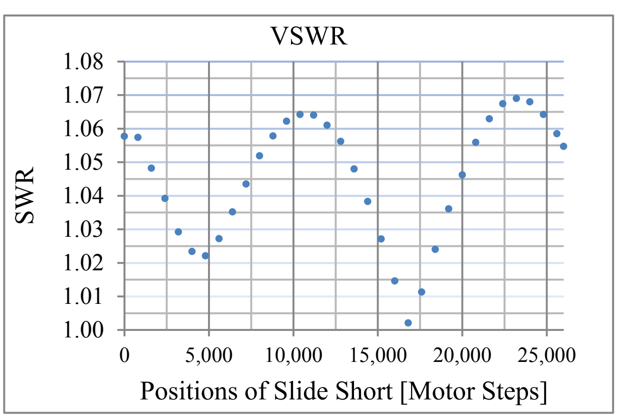

Figure 7: VSWR of the phase shifter.

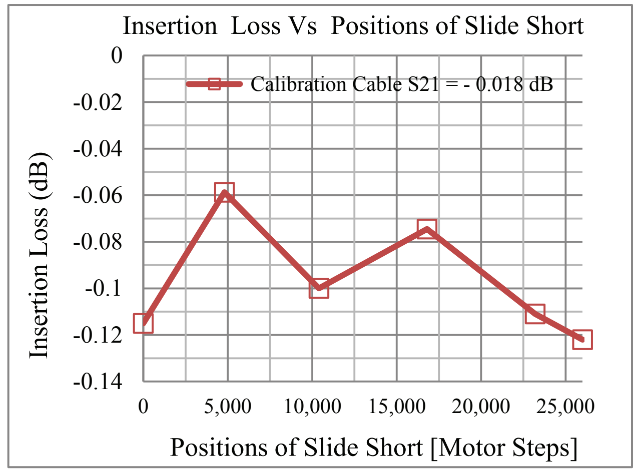

Figure 8: Insertion loss of the phase shifter.

Table 5: Phase Shifter Parameters and RF Signal Test Results

	TRIUMF Specification	**Manufacture Reports**	**RF Signal Test**
Frequency [MHz]	1300	1300	1300
Phase shift	360°	360°	360°
Phase resolution	< 0.2 °	< 0.1 °	< 0.1 °
$VSWR_{Max}$	1.06 : 1	1.08 : 1	1.07 : 1
Return loss [dB]	> 30	> 28.3	> 29.4
Insertion loss [dB]	< 0.1	0.05	0.058-0.12

High Power RF Tests of the Variable Phase Shifters

After rf level signal tests on bench, the phase shifters are installed in Klystron hall. To prevent any damages to the motors and controllers of phase shifters from x-ray, only the WR650 waveguides sections are installed in electron hall. All motor controllers, rf interlock signals, and rf power monitoring cables are installed in klystrons hall. The phase balance between two waveguide paths for rf power couplers have been tuned and reached in very precise phase. The accuracy of the phase difference between two paths is better than ±0.01 degrees. The rf level signal measurements were performed with the 3 dB hybrid and water loads fully assembled together. The water load was filled with ionized cooling water while measuring the phase balance and attenuation between the two waveguide paths simultaneously. Fig. 9 shows the phase balance of two waveguide paths for e-linac injection cavity. The phase difference between the two paths is 0.01 degrees.

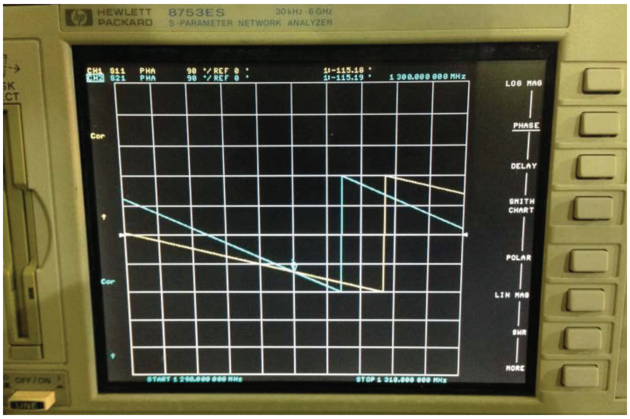

Figure 9: Phase balance between 2 paths of EINJ reached after tuning the phase shifter.

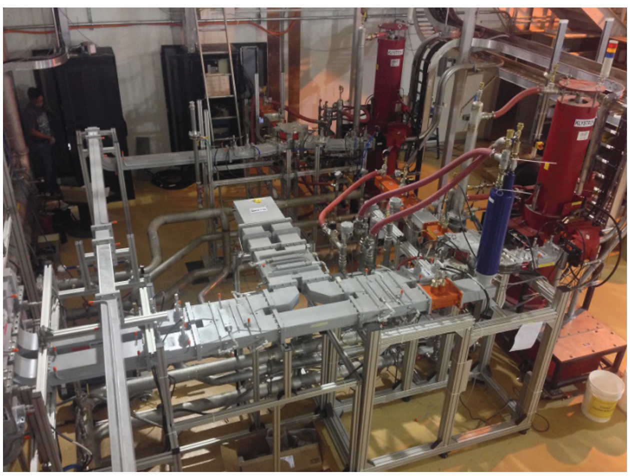
Figure 10: High power rf transmission system of e-Linac phase-I.

HIGH POWER RF TESTS AND COMMISSIONING

One klystron powered the superconducting cavity into EINJ with rf power for the first beam in May 2014. The 360^0 variable phase shifter is working well for tuning beams. As shown in Fig. 10 for the high power rf distribution system in the e-linac phase-I commissioning, September 2014, two klystrons feed rf powers to the superconducting cavities in EINJ and EACA respectively. Two waveguide phase shifters, one variable power divider, water loads and all waveguide components in functions well. The remote control to the phase shifters and the variable power divider are working stable in control room. The positions of read-back or the working parameters of them are repeatable. The phase shifters and the variable power divider have met our technical specifications and satisfied with the beam optics.

To run maximum rf power at nominal value (250 KW cw) will be our next goal, e-linac phase-II and at nominal beam intensity (10 mA). Water cooling pipes attached along the waveguides and on rf components will being run cooling water all. At that time about 250 kW cw rf power will be split into two by the power divider to accelerate beams via two superconducting cavities in each accelerating cryomodule.

CONCLUSION

Two klystrons feeding RF power into e-linac injector and accelerating section for the first step commissioning are in success. The variable phase shifters and the power divider and high power rf components are all performing very well and met the operation requirement for beams. The high power rf system performs demonstrate that the simulations and rf signal level tests of the elements met with the system specifications.

ACKNOWLEDGMENT

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