RF POWER DISTRIBUTION AND PHASING AT SSRL INJECTOR LINAC

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Abstract

At the Stanford Synchrotron Radiation Laboratory injector linac, each of three linac sections was powered by an XK-5 klystron for 5 years starting from 1990. The RF power from the second klystron was then branched out to drive the thermionic RF gun. Due to dwindling performance of XK-5's, two of them were replaced by one SLAC type 5045, which powered the RF gun and the first two linac sections. In the summer of 1997, the linac system was further modified to have one 5045 power all three sections and gun. During this process a 5dB waveguide directional coupler was developed, and RF phasing was done by cold tests and by beam-based tuning of the waveguide network at full power. The remaining two XK-5's are currently being utilized at the Gun Test Facility located in the injector linac vault to drive a photocathode gun followed by a linac.

1 INTRODUCTION

The SSRL Booster synchrotron[1] accelerates a bunch of 10^9 electrons from 100 MeV to 2.3 GeV at the rate of 10 bunches per second, which is limited by the White circuit, before it is injected to the SPEAR storage ring. When the stored beam current reaches 100 mA, the beam energy is ramped to 3 GeV for user run.

In order to maximize the injection rate in terms of mA/min, it is very important to maintain a shot-to-shot reproducibility and a long term stability of the linac beam energy, which is proportional to the square root of the RF power. To this end, all the DC voltages applied to the klystron (focusing magnet and core bias) and modulator (PFN and thyratron reservoir) are regulated through switching or linear power supplies. Constant voltage transformers stabilize the AC power to the klystron cathode and thyratron heater.

The beam voltage and the input RF power is selected in such a way that $\delta P_O/\delta P_I = 0$ when the beam voltage stays constant (output power saturation). In general, higher klystron beam voltage requires less RF input power for the RF output power to saturate. Therefore, one sets the beam voltage first and adjusts input RF power level by a PIN diode-based attenuator until the klystron output is saturated. If the power is not right for the desired linac beam energy, the klystron beam voltage is changed and the process is repeated.

Another factor that affects the beam energy is the temperature at the gun and linac. For them to stay tuned at the operating frequency of 2.856 GHz, there are two systems that supply temperature controlled water (TCW); one for the gun and the other for linac that operates in different temperature range from the gun. The temperature regulation is better than 0.1^{O}F in both systems. Considering the thermal expansion coefficient of copper at 1.7×10^{-5} / ^{O}C, the resonance frequency of both structures remains unchanged within 3 kHz.

2 RF POWER DISTRIBUTION

When 4 linac sections are powered by one klystron, which is the case with the SLAC main linac, the RF power from the klystron is divided evenly twice by three of 3-dB hybrids so that each section is driven by equal level of RF power. When the number of linac sections to be driven is three, the power needs to be divided by 1:2 ratio, then the main line is evenly divided by a 3-dB hybrid. This is how the SSRL injector linac is powered by a single klystron.

The power branching ratio of a 3-dB hybrid is 1:1, and deviation from the design value is usually very small. Any other coupling between 3 and, say, 15 dB requires multi-hole narrow wall coupler. While it is possible to achieve precision coupling in calculations, errors from the process of machining make it very hard to predict what the actual coupling would be.

Therefore, the sequence of building a high power waveguide directional coupler is to choose a design of smaller coupling. For example, if a 5-dB coupler is to be made, choose a 7-dB coupler, duplicate the coupling strip of some 10 pairs of holes. Then clamp the two waveguide pieces together, with the strip inserted in between. Take data on coupling and phase delay at the main line and coupled port. In order to increase the coupling, the width and/or the length of all the holes are to be made larger. One repeats the process of mechanical modification of the coupling holes and cold tests until the coupling is within the tolerance. The final stage is to braze all the components together. As it turns out, the brazing process does not alter the RF characteristics of a directional coupler very much.

The heart of a multi-hole directional coupler is the coupling strip. A sketch of it is shown below. The most important dimensions are A (6.016 in.= λ_g), B (=$\lambda_g/4$), and C (= 0.600 in.).

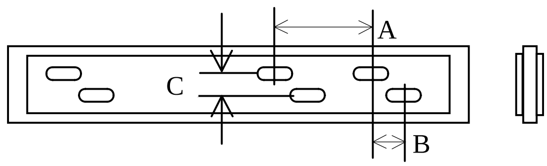

Figure 1: A coupling strip for a multi-hole narrow wall waveguide directional coupler. Only three pairs are shown for clarity. The endview is shown at the right.

This copper strip has overall dimension of 1.686 in. width, 21.632 in. long, and 0.375 in. thick. The mesa on either side is 0.086 in. above the middle part, and is to be mated with the waveguide. The holes are 0.3 in. wide rectangles, ending with a semi-circle at the ends. Each has overall length of about 1.5 inches. Typically, there are 10 pairs. If this number is reduced, directivity is also lowered. With the dimensions A, B, and C remaining the same, the hole size determines the coupling coefficient.

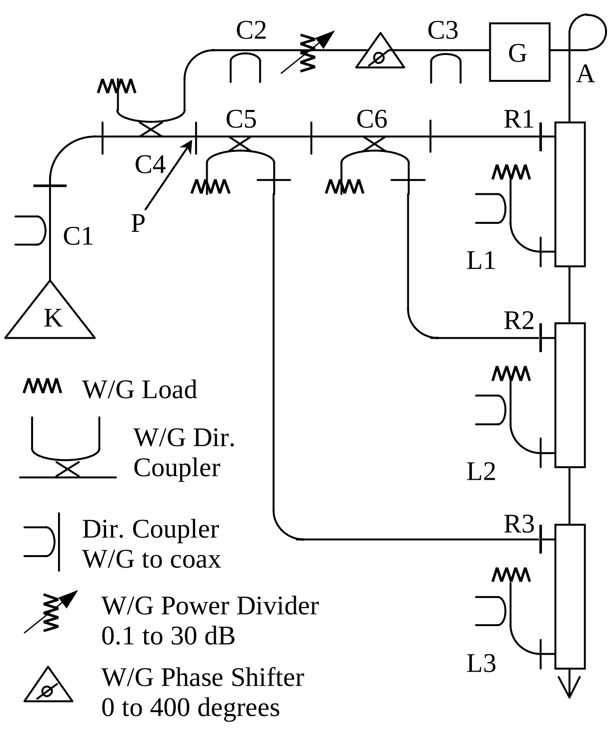

Figure 2 : The system layout of the S-band RF power distribution at the SSRL injector linac including the RF gun (G). The klystron (K) is a SLAC type 5045. The directional couplers C1 and C3 are for the power level monitoring, and C2 at 37 dB coupling is to drive another klystron, such as XK-5, for the Gun Test Facility. [2]

In the Fig.2, C4 has 8.5 dB coupling. The coupled out power is reduced by the power divider and drives the RF gun (G) at about 2 MW. The thermionic electrons bunches at about 2 MeV are compressed from about 100 ps to about 1 ps or shorter by the alpha magnet (A). At this point, there are about 3000 bunches. In order to minimize the beam loading to the linac, all but 4~5 bunches are diverted to the beam dump by the chopper (not shown). C6 in Fig.2 is a 3-dB hybrid.

The C5 measured coupling was 5.21 dB at 2.856 GHz. For the best efficiency, this should have been 4.77 dB, or exactly 1:2 branching ratio. Assuming that L1~L3 are all perfectly phased, and ignoring any parasitic losses, the energy gain by the linac is given by

$$\Delta E = 10.7\left(\sqrt{rP} + \sqrt{2P(1-r)}\right)$$

where ΔE is in MeV, r is the branching ratio at C5, and P is the RF power in MW at the C5 input. At 5.21 dB, r is $10^{-0.521}$ = 0.301 and ΔE = 117.1 MeV at 40 MW. At the same power, if r is 1/3 (4.77 dB), energy gain is 117.2 MeV. As one can notice from this example the energy dependence on the C5 coupling coefficient is very weak. If $r<1/3$, more power is available at the first two sections. If it is more, then the third section adds more to the total gain while the first two add less. Therefore the coupling requirement is then 4.8±0.5 dB.

3 RF PHASING BEWTEEN LINACS

As has been shown in the previous section, the linac energy is insensitive to how the power is divided up to drive each linac section. When it comes to the phasing, one has to be extra careful to maximize the energy at a given RF power. Here the gun is out of the picture for two reasons: one is that at about 2 MeV, the initial energy out of the gun is only a small perturbation to the total energy of the beam, which is steered into the booster synchrotron. The other is that the gun RF power is adjusted in amplitude and phase by the power divider and the waveguide phase shifter, as shown in Fig. 2.

The three linac sections are aligned to a straight line passing through the electrical centers of each. They are separated from each other by $34\lambda_0$ longitudinally, which is 140.510 inches. Then the requirement for maximum acceleration is that the RF phase must be the same at all three RF input ports. Therefore the phase lengths from the C5 input (P in Fig.2) to the L1~L3 input have to be adjusted to make them the same.

In a straight section, male (female) Skarpaas flange adds 0.641 (0.559) in. to the tip-to-tip copper waveguide length, including one half the thickness of copper gasket. In waveguide directional couplers, 3-dB hybrids, H-mitres, H- bends, and E-bends, the path length is very different from geometric length. Therefore the phase length of each individual component must be measured with a vector network analyzer in the air, to arrive at the side arm length of a U tube at the final leg of the waveguide network. Of course the vacuum inside gives rise to mechanical deformation of the waveguide that leads to a change in path length, but it is small enough to ignore in the first order.

Once all the parts are fabricated and assembled, the entire network of waveguide from C5 to male flanges for RF input to each linac sections was moved by one inch away from linac. Then modulator flanges[3] were inserted, and entire network starting from the point *P* to linac sections L1~L3 was pumped down to about 1 torr. This flange is about 0.5 inch thick. One side is Skarpaas male and the other female for vacuum seal. It has germanium diode at the center of broad side. When it is reverse biased at –20V at 1 kHz it causes total reflection.

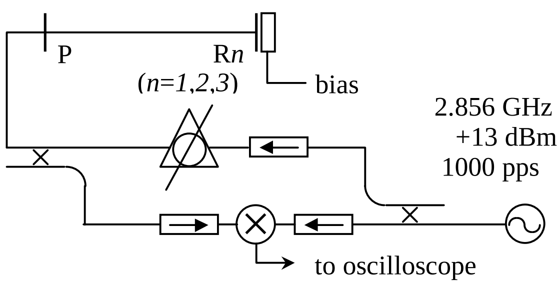

Figure 3 : Circuit diagram for phase measurement of the reflected wave, for P to R*n* path lengths.

By adjusting the phase shifter, the mixer output can be made zero. If the phase shifter setting is $\phi 1$ for n=1, the difference in phase readings shows the phasing error of each branch. The error correction is done by squeezing the waveguide wall. The guided wavelength of RF is

$$\lambda_g = \lambda_0 / \sqrt{1-(\lambda_0/2a)^2}$$

where a =2.840 in. is the inside dimension of broad wall. By squeezing the narrow wall to make a smaller, the guided wavelength λ_g is made longer. If broad wall is squeezed, it forces the narrow wall to bulge out resulting in a shorter λ_g. This procedure is performed using a C-clamp while monitoring the null on oscilloscope. The accuracy of this method is better than $\pm 4^o$ of RF phase.

At the conclusion of the process above, it was found that one modulator flange was inadvertently reversed in direction. After the commissioning, additional efforts were made to correct the error caused by the mistake. Hardware was assembled around the waveguide inside the linac vault, to have it squeezed by hydraulic jacks operated from the outside, while the system is up to full power. The assembly consists of two pairs of steel bars (one inch square, 12 inches long, and tapered 3 inches both ends), aluminum holder, two hydraulic jacks, two dialed indicator gauges, and a TV camera to read the gauges. For better reliability and safety, a phase bridge was made to monitor incremental phase as shown below.

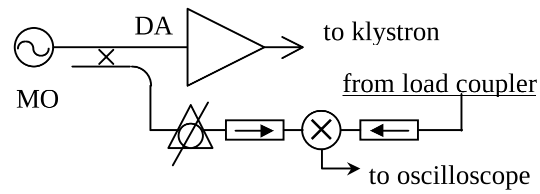

Figure 4: Linac incremental phase monitor. The master oscillator (MO) has +14 dBm cw output. The drive amplifier (DA) has 7μs pulse length at 10 Hz.

The manual phase shifter was set to produce a null reading. Then setting was changed by 2.856^o, to be nulled by squeezing the waveguide remotely. At every step of phase correction, the linac beam energy was measured by a bending magnet. The ΔE plot against $\delta\phi$ was close to a sine curve. At the end, the energy gain from the phase correction was peaked at 2.5 MeV.

4 CONCLUSION

The linac system has been modified to have one klystron drive the RF gun and all three linac sections for improved stability and reliability. A 5-dB coupler was produced for the purpose. Now it became possible to design and fabricate precision high power directional coupler of any coupling coefficient through interpolation of existing designs and analyzer measurements prior to assembly. RF phasing between klystron and linac sections was accomplished locally at low power (20 mW), and remotely at full power (40 MW), to achieve highest possible linac beam energy for a given klystron output power.

5 ACKNOWLEDGEMENT

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6 REFERENCES

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