RECONFIGURABLE HIGH-POWER RF SYSTEM IN THE APS

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Abstract

The 352-MHz high-power system for the Advanced Photon Source (APS) storage ring and booster synchrotron has been configured to allow two to four klystrons to power the storage ring and one klystron to power the booster. A quadrature hybrid combines two klystron outputs with two 45° phase shifters at each output of the hybrid for proper phasing at the storage ring cavities for the selected mode. The phase shifters in the hybrid outputs and three waveguide switches are used to choose an operation mode in any one of twelve possible configurations using three to five klystrons to power the storage ring and booster. The system can be configured to use one klystron as the power source of a test station.

1 INTRODUCTION

For reliable and continuous operation of the booster synchrotron and the storage ring of the APS, a reconfigurable high-power rf system is needed. The goal is to have a system that is operational even with one or two klystrons turned off for maintenance or other tasks such as high-power conditioning or testing of other rf components.The APS high-power rf system consists of five rf stations: one for the booster and the other four for the storage ring. Each rf station consists of one 1.0-MW klystron and a 95-kV, 20A DC power supply. The storage ring has four rf sectors and each sector has four uniformly spaced single-cell cavities. All sixteen cavities in the storage ring need to be powered for reliable beam quality. Therefore, a way of combining two or more klystron outputs and splitting the combined rf power to the sixteen cavities has been implemented.

The design of the waveguide switching system for rf power distribution in the APS is shown in Figure 1. The 90° quadrature hybrids and 45° phase shifters in the WR2300 waveguide are used as the elements for combining and splitting the power. Other hybrids, such as 180° or magic tee types, have been used [1], but the availability of the hardware and lower phase shifting requirements made the present design attractive.

The switching system is equipped with an equipment safety interlock system through an rf power monitoring system. The system is controlled by a programmable logic controller (PLC) unit independent from the main computer control system of the accelerators. The waveguide circuit has been completely installed and has powered the booster and storage ring systems successfully.

2 OPERATION

In Figure 1, klystron outputs of the RF1 and RF4 stations are combined through a hybrid and feed cavities in sectors 38 and 40. Klystron outputs of RF2 and RF3 are combined through a hybrid and feed cavities in sectors 36 and 37. The hybrid output feeds a sector with four single-cell cavities. The system includes all five klystrons (RF1-RF5) for the booster and storage ring of the APS. For the storage ring, one or more klystrons may be turned off, but not the two for one hybrid. For the booster, RF3 can be used when RF5 is not available. RF1 may be switched to the test station; RF4 alone feeds sectors 38 and 40. Each klystron output is connected to the hybrid through a 1MW, three-port ferrite circulator that is used as an isolator with a water load in the isolation port. Basic operation and construction of the waveguide system design are discussed below.

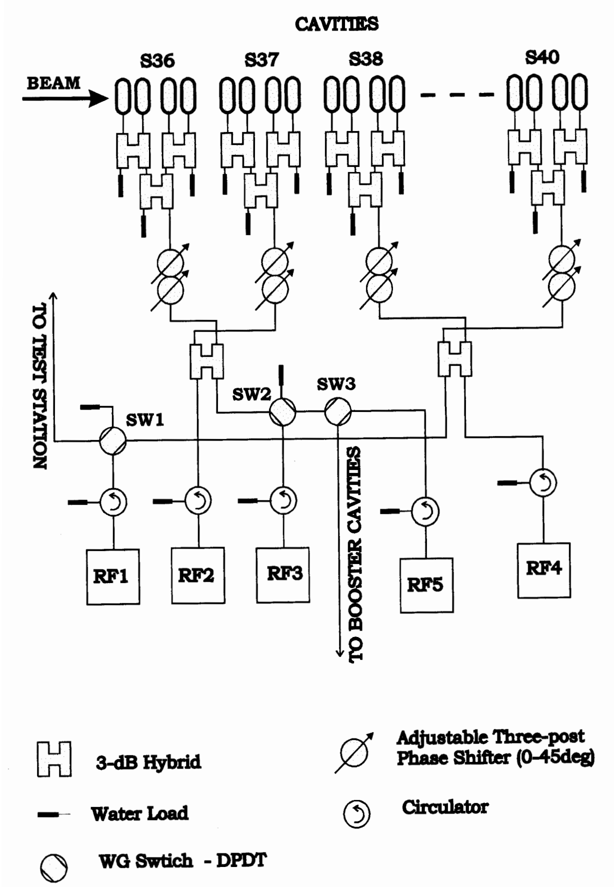

Figure 1: Reconfigurable waveguide switching system.

Figure 2 shows a part of Figure 1 where a 90° quadrature hybrid combines two inputs from two klystrons through circulators and splits into two outputs with two adjustable output phase shifters. For convenience, one phase shifter is shown in each output arm in Figure 2 instead of two as in Figure 1.

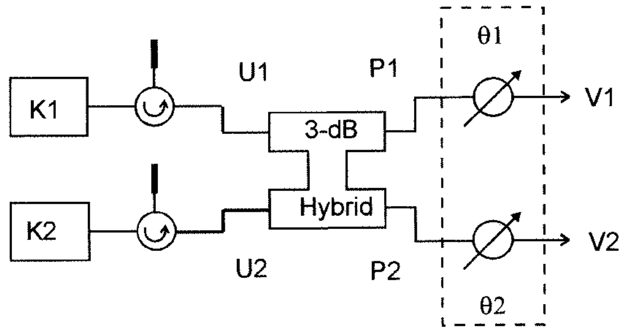

Figure 2: Two klystron-two sector feeding through a hybrid.

With two input port voltages of the quadrature hybrid $U_1 = \sqrt{2}ae^{j\omega t}$ and $U_2 = \sqrt{2}be^{j\omega t}$, the combined hybrid output rf voltages through the phase shifters are superpositions of split outputs from each input and can be expressed as

$$V_1 = \left(ae^{j\omega t} + be^{j\omega t}e^{-j\frac{\pi}{2}}\right)e^{-j\theta_1}$$

$$= ce^{j(\omega t - \phi_1 - \theta_1)} \quad (1)$$

$$V_2 = \left(ae^{j\omega t}e^{-j\frac{\pi}{2}} + be^{j\omega t}\right)e^{-j\theta_2}$$

$$= ce^{j(\omega t - \phi_2 - \theta_2)} \quad (2)$$

where $c = (a^2 + b^2)^{1/2}$, and the phases $\phi_1 = \mathrm{atan}(b/a)$ and $\phi_2 = \mathrm{atan}(a/b)$. For identical output phases, the phase difference between the two phase shifters is expressed as

$$\Delta\phi = \phi_1 - \phi_2 = \theta_2 - \theta_1 \quad (3)$$

$$\Delta\phi = \mathrm{atan}(r) - \mathrm{atan}\left(\frac{1}{r}\right) \quad (4)$$

where the power ratio r = b/a. The differential phase with respect to the input power imbalance is

$$\frac{d(\Delta\phi)}{dr} = \frac{2}{(1 + r^2)} \quad (5)$$

where $\Delta\phi$ is shown with respect to the amplitude ratio r in Figure 3. Note that the abscissa is in logarithmic scale. Using Eq. (5), phase fluctuation between sectors is found as ~0.6°/1% amplitude difference between the two klystrons when $a \approx b$.

In Figure 2, three configurations are possible; these cases can be compared in terms of the phase requirement at the hybrid outputs. The three cases are 1) both K1 and K2 are turned on, 2) only K1 is turned on, and 3) only K2 is turned on.

For delivery of rf power with specified phase relations at the cavities, the phase shifters must be adjusted properly. The phase shift requirements for the three different cases described above are as follows:

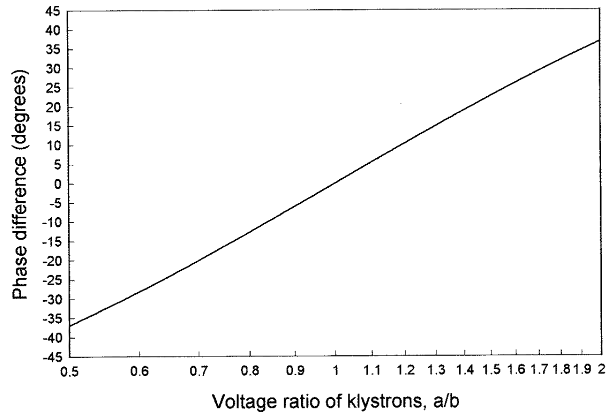

Figure 3: Phase difference between two outputs vs. the input power imbalance.

1. If a = b,

$$V_1 = \sqrt{2}ae^{j\left(\omega t - \frac{\pi}{4} - \theta_1\right)}, \quad V_2 = \sqrt{2}ae^{j\left(\omega t - \frac{\pi}{4} - \theta_2\right)}$$

$$\theta_1 = \theta_2 = 45°$$

2. If b = 0,

$$V_1 = ae^{j(\omega t - \theta_1)}, \quad V_2 = ae^{j\left(\omega t - \frac{\pi}{2} - \theta_2\right)}$$

$$\theta_1 = 90°, \ \theta_2 = 0°$$

3. If a = 0,

$$V_1 = be^{j\left(\omega t - \frac{\pi}{2} - \theta_1\right)}, \quad V_2 = be^{j(\omega t - \theta_2)}$$

$$\theta_1 = 0°, \ \theta_2 = 90°$$

Note that, if all cavities are matched, there is no reflected power. If any backward traveling wave exists due to cavity mismatch or coupled cavity higher-order modes, it can be absorbed by the loads on the isolation ports of circulators.

3 CONFIGURATION

Table 1 shows the possible configurations for the switching system. A minimum of two klystrons are used for supplying the needed rf power to the storage ring cavities. However, for two-klystron operation, each hybrid must be powered by one klystron to feed all sixteen cavities. The system is reconfigurable to one of the twelve modes by moving a key in a bank of keyswitches, which provides a mode change signal to the PLC. All waveguide switches, phase shifters, power monitors, and safety interlocks are switched to position with a movement of the key.

3.1 Waveguide Switch

The waveguide switches are a motor-driven vane type with spring contacts between the vane and the waveguide wall and limit-switches. These waveguide switches do not contribute to any phase shifting but direct the rf power to other systems. The equipment safety interlock system assures that no hot switching is made while rf power is present in the waveguides. Directional couplers are placed on each arm of the switches to detect any rf signal above a threshold.

Table 1: RF System Operation Switching Modes

RF System Status				
Mode	System Energized			Down
	Storage Ring	Booster	Test Station	
1	RF1, RF2, RF3, RF4	RF5		
2	RF2, RF3, RF4	RF5	RF1	RF1
3	RF1, RF3, RF4	RF5		RF2
4	RF1, RF2, RF4	RF5		RF3
5	RF1, RF2, RF3	RF5		RF4
6	RF1, RF2, RF4	RF3		RF5
7	RF2, RF4	RF3	RF1	RF1, RF5
8	RF1, RF2	RF3		RF4, RF5
9	RF1, RF2	RF5		RF3, RF4
10	RF3, RF4	RF5	RF1	RF2, RF1
11	RF2, RF4	RF5	RF1	RF3, RF1
12	RF1, RF3	RF5		RF2, RF4

3.2 Phase Shifter

The three cases for phasing shown in section 2 above can be achieved by using adjustable phase shifters. For the waveguide switching system, motorized three-post phase shifters have been used to properly phase the cavities in the four rf sectors. The three-post phase shifters are not expensive and are readily available from several vendors. However, since the adjustable phase range of a single phase shifter is about 50°, two phase shifters must be connected in series to form a 90° phase shifter at each output of the hybrids. A total of eight 45° three-post waveguide phase shifters are used in the system. Micro-limit switches are preset for a 0°-45° shifting range. Again, the control interlock system assures no hot shifting is made while the rf power is present.

4 DISCUSSION

So far, the system has run in a few different two-klystron modes without problem. The klystron powers are ~600 kW for a 100-mA beam current. With two klystrons in a hybrid, for the modes with three or four klystrons, the hybrid outputs need to be controlled to have a certain phase stability that can directly affect cavity rf phases and, therefore, the beam. The klystrons are being equipped with AC-coupled feedback loops for uniform power outputs to minimize the effect of amplitude-phase conversion and offset phase control to maintain proper inter-station phase when operating klystrons in parallel. This rf control is somewhat similar to the system implemented for the LEP system [2]. A test station is needed for various reasons and rf station RF1 can be used for this purpose. Other arrangements can be used for the phase shifting with fixed phase shifters. In this approach, each hybrid needs four fixed-length waveguide sections—two 0° and two 45°—and three double-pole waveguide switches. This method costs more since the waveguide switches are more expensive than the waveguide phase shifters.

5 CONCLUSION

The system has been completely tested for mode selection and interlocks and has been running in a few different modes without problem. The need for feedback control in the hybrid inputs raises the question of the system's stability and reliability. Since the rf signal input phases through the driver amplifiers to the klystrons can be tightly controlled, it is anticipated that the system can be made stable and reliable. Reliability of the high-power system has been improving steadily in the APS. Additionally, the maintainability has improved with the increased accessibility and flexibility of the system. Installation and testing of the klystron feedback control for the configurations with three or more klystrons remains to be done.

6 ACKNOWLEDGMENT

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7 REFERENCES

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