General Overview of the APS Low–Level RF Control System*

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Abstract

This paper describes the proposed low–level rf system of the positron accumulator ring (PAR), the injector synchrotron, and the storage ring of the 7–GeV Advanced Photon Source. Four rf systems are described since the PAR consists of a fundamental frequency system at 9.8 MHz and a harmonic system at 117 MHz. A block diagram of an accelerating unit is shown and descriptions of various control loops are made (including amplitude control, phase control, and cavity tuning control). Also, a brief overview of the computer interface is given.

I. POSITRON ACCUMULATOR RING (PAR)

There are two rf systems in the PAR. One operates at 9.8 MHz to collect the linac pulses, and a second operates at 118 MHz for the last 100 ms of the 2–Hz injection cycle to bunch the beam until extraction. Each system consists of one cavity, one rf amplifier, and associated control circuitry. The control system also synchronizes operation with the linac during injection and with the synchrotron during extraction.

TABLE I. FUNDAMENTAL PARAMETER LIST

Frequency	9.77584 MHz
Harmonic Number	1
Peak Voltage	40 kV
Power	4.7 kW
Cavity Type	Cap–loaded Coaxial
Number of Cavities	1
Cavity Tuning	Electronic
Control Loop Bandwidth	10 kHz
Transit Time (2Q/w)	248 μs
Phase Detector Resolution	1.0 degrees

9.8–MHz System

The slow thermal tuning of the 9.8–MHz cavity will be accomplished by a coarse tuner. A fast tuner will be accomplished by ferrite.

Since beam loading is incremental, with 24 linac bunches injected over a 400–ms period, a modest feedback control system keeps the cavity voltage constant and the power amplifier load impedance real. (Control parameters are listed in Table I.) Programming of the power amplifier input voltages and fine tuning of the cavity are included to offset the transient from each injected bunch.

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TABLE II. TWELFTH HARMONIC PARAMETER LIST

Frequency	117.3101 MHz
Harmonic Number	12
Peak Voltage	30 kV
Power	1.82 kW
Cavity Type	λ/2 coaxial
Number of Cavities	1
Cavity Tuning	Electronic and Mechanical
Control Loop Bandwidth	10 kHz
Transit Time (2Q/w)	68 μs
Phase Detector Resolution	1.0 degrees

117–MHz System

The cavity is electronically adjusted during operation of the 9.8–MHz cavity so as not to interact with the beam, since only the fundamental cavity is used during accumulation.

A 2–kW amplifier is located outside the shield wall, and the cavity is powered via coaxial cable. Resistive loading is included by using a stainless steel cavity. The rf power is then equal to the beam power giving a maximum detuning of 45 degrees. If rf feedback is needed, this amplifier could be mounted on the cavity to minimize phase delay at 117 MHz. [1]

When the cavity is switched from a passive (imitating a beam pipe) to an active state, beam loading is rapid. A fast tuning and voltage control system, including feed–forward techniques, is used, and large induced voltages are avoided with programmed tuning. The amount of circulating beam controls the program signals to the power amplifier and to the tuning device, so that as the cavity is turned on for the last 50 ms of the PAR cycle, the accelerating voltage has the correct phase with respect to the 9.8–MHz bucket and the power amplifier sees a real load. Using a programmed correction signal improves the operation of the cavity; thus, for a given tolerance of cavity parameters, the feedback loop dynamic range and gain can be smaller. The correction signal is derived from the bunch signal from the master clock.

The rf amplifier produces a 30–kV accelerating voltage. Since only 222 Watts is needed to power a copper cavity, resistive loading is provided via the stainless steel cavity which lowers the shunt impedance and reduces the phase shift between beam current and generator current. This makes the programming and feedback systems less sensitive to variations in beam loading and increases the stability of the feedback system. Parameters for operation are listed in Table II.

The frequency source for the PAR system is a frequency division of the 351.9–MHz storage ring frequency source. The signal is first divided by 3 to generate a 117–MHz source which is phase–shifted to allow placement into one of three buckets at –120°, 0°, or +120°. This signal is then further divided by 12 to produce the 9.8–MHz signal. Using this method, all three frequency sources are phase coherent with the storage ring frequency source.

II. BOOSTER SYNCHROTRON

The low–level system generates the rf signal to drive a klystron amplifier. The synchrotron signal generator is phase–locked to the storage ring master oscillator. The storage ring rf signal is transmitted to the synchrotron signal generator over phase–stabilized cable.

The low–level system also includes the analog phase and amplitude regulation systems that maintain the cavity rf voltages. Figure 1 shows this schematically for one of the systems of the storage ring, and Table III lists specific parameters.

TABLE III. BOOSTER PARAMETER LIST

Frequency	351.930 MHz
Harmonic Number	432
Revolution Frequency	814.3 kHz
Repetition Time	0.5 s
Acceleration Time	0.25 s
Cycle Rate	2 Hz
Peak Voltage for 7 GeV	9.5 MV
Injection Voltage	100 kV
Peak Power	700 kW
Cavity Type	5–cell
Number of Cavities	4
Cavity Tuning	Dual Piston/Motor
Amplifier	Klystron
Synchrotron Frequency	21.1 kHz
Phase Detector Resolution	0.1 degrees
Dynamic Range	40 dB Volts

A single 1–MW klystron drives four five–cell cavities. The cavities are separated into two groups of two each, on opposite sides of the ring. The second and fourth cells are fitted with ports for the tuners which provide amplitude and phase balance. The tuner slugs are fitted to worm gears and stepper motors which provide 1 µm of step resolution. A feedback system monitors the phase difference in the cavity and adjusts the tuners in tandem to keep the cavity at the resonant frequency with +/– 0.1 ° under rf heating. Also, the field amplitudes in each of the two cells are detected and the tuners are adjusted differentially to balance the voltage to within +/– 1 dB.

The klystron output is monitored and a feedback system is used to eliminate the power supply ripple and phase variations due to cathode voltage variations. The rf drive signal is modulated in amplitude and phase.

Each cell of the cavity has a field monitor. The tuner–port cells derive the field–balance signal. The end cell fields are added in phase to derive the average cavity phase and control both tuners in parallel. The resultant signal is compared to the driving signal with a phase meter. For slow tuning, the digital phase information goes to the control computer to offset the tuners for rf heating by varying the water temperature. For fast tuning a copper tuner piston is activated by a stepping motor controlled by a servo amplifier system. The feedback loop that drives the tuning piston works on only the reactive element of the cavity input impedance. Since the beam loading is so small, no de–tuning is foreseen to accommodate the "Robinson Stability" criteria. [2] The computer then controls the offset of the two tuners of each cavity to keep it properly tuned.

Waveguide Phase Shifter

A mechanical waveguide phase shifter is located in the feedline to the more distant pair of 5–cell cavities. This phase shifter adjusts the rf phase to be the same in both the nearer and farther pairs of 5–cell cavities regardless of temperature variations within the building.

The storage ring rf signal is transmitted to the synchrotron over phase–stabilized coaxial cable from the rf source cabinet. This ensures phase continuity with the storage ring.

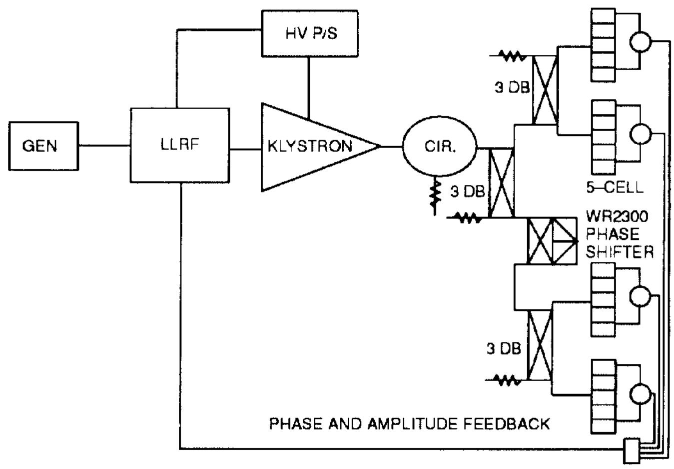

Figure 1. Synchrotron Block Diagram

III. STORAGE RING

The low–level rf system controls the amplitude and phase of the rf signal which drives the klystron amplifier. It also includes the tuning regulation that maintains each cavity's resonance point. See Table IV for specifications.

TABLE IV. STORAGE RING PARAMETER LIST

Frequency	351.93 MHz
Revolution Frequency	271.5 kHz
Harmonic Number	1296
Filling Time, Multibunch	0.9 min
Filling Time, Single	2.7 s
Cavity Type	Single–cell
Number of Cavities	16 in 4 groups
Cavity Tuning	Piston/Motor
Amplifier	1 MW Klystron
Number of Amplifiers	4
Cavity Peak Voltage	600 kV
Synchrotron Frequency	1.96 kHz
Phase Detector Resolution	0.1 degrees
Control Loop Bandwidth	1 kHz

The low–level rf system consists of five different control loops. An rf drive control loop is used to set the gap voltage across the storage ring cavities. A klystron operating loop is used to set the operating level of the klystron in the linear or saturation region. A cavity tuning loop is used to keep the cavity input impedance real during beam loading and rf heating. The loop moves a tuner piston through a stepper motor which changes the inductance of the cavity. A klystron phase control loop keeps the output phase constant due to changes in voltage and power levels. A cavity phase control loop keeps the sum of the phases of all the cavities constant for proper synchronous phase operation.

The input to each klystron amplifier driver has a computer–controlled rf amplitude modulator and a computer–controlled relative phase shifter. An amplitude comparator compares the sum of the voltages from all cavities to a reference, and adjusts the rf modulator to maintain the required voltage. The phase of the voltage developed in the cavities is compared with the reference, and the phase of the drive to the klystrons is adjusted to maintain the cavity voltage phase to $<1.0^\circ$.

The klystron power is controlled by a control loop through the modulating anode system, while the klystron operating point is maintained in the linear gain region. In this way the klystron efficiency remains optimum. [3]

The cavity tuner port has an 11.5–cm diameter and a 6.0–cm travel. This results in a frequency tuning range of 1.0 MHz to compensate for beam loading, temperature effects, etc. The copper plunger is activated by a stepping motor controlled by a servo amplifier system. The feedback loop that drives the tuning piston works on only the reactive element of the cavity input impedance.

Beam Compensation

Compensation for the reactive component of the beam loading is done prior to injection by detuning to comply with the requirement of the Robinson instability criterion. For the APS storage ring cavity this amounts to a negative 16 kHz of detuning from the no–beam resonance condition to the fully loaded condition. After beam filling is completed the cavities are tuned closer to resonance, and the Robinson instability is counteracted with dynamic feedback via the low–level feedback system.

V. COMPUTER INTERFACE

The rf system is under active computer control and is continuously monitored by computer. Each cavity has a field monitor. The monitors are added in phase, and the resultant signal is compared to the driving signal with a digital phase meter. The digital phase information goes to the control computer which adds the required offset to satisfy the requirements of the Robinson stability criteria. The computer then controls both tuners of each cavity to keep it properly tuned.

The computer interface, in real time, reads the phase of the voltage developed in each storage ring cavity relative to the input phase, the phase error of the klystron output power relative to the input drive phase, and the gap voltage developed across the cavity. This phase is compared to the phase of the power into the cavity. The computer drives the tuner stepper motor to maintain the required relationship to satisfy the requirements of the Robinson stability criteria.

Each control loop has local operation and diagnostics as well as a computer bus interface for remote operation and diagnostics.

The computer interface additionally monitors the operating environment of the klystron, circulator, and cavity. This includes water flow, air flow, temperature, and cavity vacuum, and warns of "out of tolerance" operating conditions and shuts off components if necessary.

The computer interface will also regulate the klystron beam voltage and current (through the modulating anode control element) to keep enough power in the klystron beam for efficient conversion to rf power for different amounts of stored beam.

VI. RF SOURCE

The frequency and phase of the storage ring rf system affect the beam position and energy. The main frequency source, a 10–MHz temperature–controlled oscillator, is stable to several parts in 10^{11} with phase continuity. A stability of 10^7 is needed for storage ring operation (see Table V). The low–level rf system utilizes a direct digital synthesizer to control a phase–locked, voltage–controlled oscillator as the source for the storage ring. The output of this common frequency source is fed via phase–stable cables to each of the klystron amplifiers in the system as well as to the synchrotron, PAR, and clock distribution for the kicker magnets.

TABLE V. RF SOURCE PARAMETERS

Operating Frequency	10.0 MHz
Output Frequencies	9.77 MHz
	117.3 MHz
	351.9 MHz
Long–Term Stability	10^{-11}/day
Short–Term Stability	10^{-9}/s
Phase Noise @ 1 kHz Offset	–100 dBc/Hz
Distance to Stations	300 ft.
Phase Stability	0.1 degrees
Minimum RF Output Power	+20 dBm

Two types of rf distribution subsystems are a star configuration [4] and a serial configuration [5]. Both provide phase stable rf signals to the multiple cavities located an appreciable distance from the rf source. The star configuration will be used to feed rf to the storage ring and synchrotron.

V. REFERENCES

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