THE RADIO FREQUENCY ACCELERATING SYSTEM OF THE APS AT ARGONNE*

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Argonne National Laboratory is constructing a 7-GeV Advanced Photon Source (APS). The RF systems of the APS include 10-MHz and 120-MHz systems for the Positron Accumulator Ring (PAR), a multicell 352-MHz system for the booster synchrotron, and a system of mode-damped, single-cell 352-MHz cavities for the storage ring.

Introduction

The positron beam is injected from an S-band linac into the PAR, bunched at the 36th and 3rd subharmonics of the synchrotron and storage ring RF frequency (351.9 MHz). Then it is injected into the synchrotron, accelerated to 7 GeV, and transferred to the storage ring. Table I lists the parameters of the various RF systems.

Table I
DESIGN REQUIREMENTS FOR THE APS RF SYSTEMS

	Frequency MHz	Peak Voltage/Turn	Shunt Impedance Per Cavity	Number of Cavities	Total Required Power
PAR	9.8	40 kV	170 kΩ	1	4.7 kW
	117.3	30 kV	2020 kΩ	1	0.22 kW
Synchrotron	351.9	10.4 MV	65 MΩ	4 5-Cell (LEP TYPE)	625 kW
Storage Ring	351.9	8.5 MV	11 MΩ	15 Single Cell	2700 kW

Positron Accumulator Ring RF System

There are two RF systems in the PAR. One operates at 9.8 MHz and the other at 117 MHz. The control system also synchronizes operation with the linac during injection and with the injector synchrotron during extraction. The system is similar to that of PIA.[1]

The linac beam is injected into the 9.8-MHz bucket. The synchronous phase angle is about 175° to compensate for radiation loss while the bunch is damped. When the bunch is damped sufficiently, the 117-MHz system is turned on and further damping occurs until extraction.

The 117-MHz system is deactivated during the first 450-ms of the 500-ms PAR cycle to prevent self-bunching of the beam at 117 MHz.

The 9.8-MHz System

The 9.8-MHz cavity is a folded quarter-wavelength, coaxial re-entrant type that is capacitively loaded to resonate at a frequency of 9.8 MHz.

The cavity is made of aluminum with a ceramic cylinder across the accelerating gap for vacuum isolation. Only the beam tube is evacuated, keeping the vacuum system cost low and avoiding multipactoring problems in the bulk of the cavity. Fine tuning will be done by a capacitive adjustment located at the loading capacitor.

The power amplifier is located outside the shield wall but close enough to the cavity to minimize resonances in the transmission line.

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. Programming of the power amplifier input voltage and cavity fine tuning is included to offset the transient from each injected bunch. Feed-forward techniques can be added if necessary.

No higher-order-mode (HOM) suppression is included, although ports are available and could be used for mode-damping circuits.

The 117-MHz System

The 117-MHz cavity is a half-wavelength coaxial cavity slightly foreshortened by the accelerating gap capacitance. The cavity is made of aluminum, with the vacuum seal at the accelerating gap to minimize the vacuum volume and multipactoring difficulties. The cavity is tunable over a range of 1 MHz.

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 the injection time of the PAR cycle. PIN diodes are used to connect resistors coupled to the cavity to lower the gap impedance by at least a factor of ten. If needed, the resonance is shifted away from 117 MHz by similar PIN diode switches connecting a reactance into the cavity. Also, higher-order-mode suppression is implemented so that the beam is undisturbed during operation of the cavity.

Injector Synchrotron Radio Frequency System

The injector synchrotron rf voltage is provided by four five-cell cavities operating at the storage ring frequency of 352 MHz, the 432nd harmonic of the revolution frequency. Injection is into a stationary bucket with a peak voltage of 100 kV. The rf voltage increases to match the synchrotron radiation losses. At extraction, the rf voltage is 10.4 MV, and the synchrotron radiation loss per turn is 6.33 MeV. The energy gain per turn is negligible compared with the synchrotron radiation losses. Table II lists the rf related parameters of the synchrotron. The four cavities are driven by a single 1-MW klystron identical to those used for the storage ring.

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Table II INJECTOR SYNCHROTRON RF PARAMETERS

PARAMETER	Value
Circumference (m)	368.0
Revolution Time (μs)	1/229
Injection Energy (GeV)	0.45
Nominal Energy (GeV)	7.0
Maximum Energy (GeV)	7.7
Repetition Time (s)	0.5
Acceleration Time (s)	0.25
Energy Loss per Turn at 7 GeV (MeV/turn)	6.33
Average Beam Current (mA)	4.8
Energy Gain per Turn (keV)	32.0
RF Parameters	
Frequency, f (MHz)	351.929
Harmonic Number, h	432
Voltage, V, at 7 GeV (MV)	8.3
Synchrotron Frequency, F_s at 7 GeV (kHz)	21.2

353-MHz Radio Frequency Cavity

The cavities for the 352-MHz injector synchrotron rf system are essentially copies of the LEP/PEP[2,3] five-cell, λ/2 resonant cavity. They have a 10.0-cm diameter beamhole with a reentrant nose. The cell length is λ/2 (42.49 cm). The radius from the center line to the inside of the outer shell is 30.2 cm. The cells are magnetically coupled with two off-axis slots. The structure is loop-excited in the center cell using a post-coupler from the WR2300 waveguide. Tuners are provided in the two cells adjacent to the center cell. Vacuum separation between the waveguide and the cavity is provided by a cylindrical ceramic window surrounding the waveguide post. The cavity body is made from forged disks and forged seamless cylinders of copper. These are machined to close tolerances and electron-beam welded.

A list of parameters for the cavity is given in Table III. The four 352-MHz cavities are divided into two groups and placed on diameterically opposite sides of the synchrotron.

Table III
PARAMETERS FOR THE FIVE-CELL, λ/2, 352-MHz CAVITY

Bore-Hole Diameter	10.0 cm
Cell Length (center line to center line)	42.49 cm
Cell Length (inside of cell, wall to wall)	38.9 cm
Cell Radius	30.2 cm
Number of Cells	5
Active Length of Cavity	2.12 m
Total Length of Cavity	2.32 m
Shunt Impedance	26.1 MΩ/m
Average Accelerating Voltage	1.39 MV/m
rf Power @ 2.95 MV/cavity	136.9 kW

352-MHz Radio Frequency Power System

The 352-MHz system for the injector synchrotron is essentially the same as the 352-MHz rf system for the storage ring. The same kind of klystron is used, but optimized to achieve a maximum efficiency of 65-70% at 700 kW instead of 1 MW. Circulators are provided to protect the klystron. Phase shifters are used to adjust the phase to the cavities.

Storage Ring Radio Frequency System

Introduction

The rf system must provide adequate voltage and power to compensate for synchrotron radiation from the dipole magnets and the insertion devices, excitation of parasitic modes by the beam, and overvoltage for an adequate beam lifetime. Design limits in the storage ring rf are: (a) 200 kW of rf power per ceramic window and (b) 800-kV accelerating voltage per cavity. The nominal frequency of operation for the storage ring rf system is 352 MHz.

The rf system uses 15 single-cell, spherical cavities. These are the same type of cavities used on the Photon Factory in Tsukuba[4] and the SRS in Daresbury.[5] Three 1-MW klystrons provide the rf power. The power from each klystron drives five cavities. Each group of five cavities is located in a 6-m straight section; these are located in the 9th, 10th, and 29th straight sections after the injection straight section. Third-harmonic cavities, operating at 1056 MHz and 1.8 MV, are being considered as a bunch length control system. The rf parameters are listed in Table IV.

Table IV RADIO FREQUENCY PARAMETERS
FOR 7-GeV AND 100-mA OPERATION

Frequency	351.929
Harmonic Number	1296
rf Voltage	9.5 MV
rf Voltage per Cavity	633 kV
Number of Single-Cell Cavities	15
Synchrotron Radiation Loss per Turn (bending Magnets)	5.45 MeV
Parasitic Voltage Loss	0.20 MV
Voltage for Insertion Devices	1.25 MV
sin ϕ_s	0.73
Number of Klystrons	3
Power at 7 GeV and 100 mA	1.27 MW
Installed Power	3.0 MW
With 5.0 mA per Bunch:	
Energy Spread, σ_E/E	0.29×10^{-2}
Bunch Length, σ_L	17.5 mm
rf-Bucket Height, $\Delta E_{rf}/E_0$ (with ID and estimated parasitic losses)	2.0% = 7 σ_E/E
Synchrotron Frequency	1.96 kHz

352-MHz Accelerating Structures

Figure 1 shows the cross section of the single-cell cavity used for the storage ring. The design was done using URMEL.[6] Estimates made by scaling from the Photon Factory measurements indicate that a single cavity can develop 800 kV with 62 kW of copper loss and with a peak electric field at the copper surface of 5.9 MV/m. The same fabrication technique used for the Photon Factory cavities is used. The cavity is machined in two halves from solid blocks of Oxygen-Free High Condutivity (OFHC) copper, with cooling channels machined into each component. The inner surfaces are machined to a high surface finish and the two halves silver-brazed together. Stainless steel vacuum flanges are fitted to the beam ports.

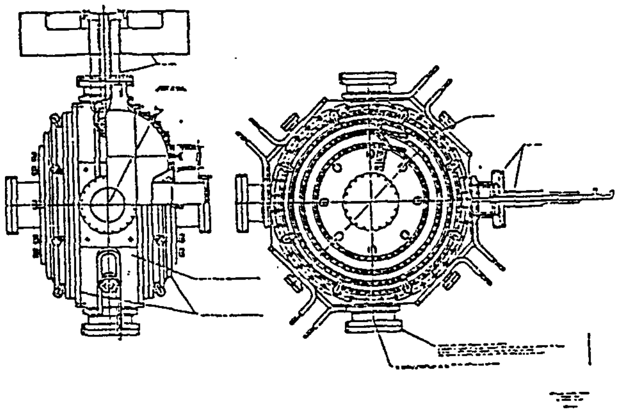

FIGURE 1 Storage Ring Single Cell Cavity Showing Input Coupler and Tuner.

Each cavity is provided with four 14-cm- and two 12-cm-diameter ports. One port is used for the coupling loop. The coupling loop, which is post-excited from a WR2300 waveguide, provides for coupling-coefficient adjustments. The post is vacuum-sealed from the air-filled waveguide by a cylindrical ceramic window. The second port is provided with a tuning plunger. The plunger has an 11.5-cm diameter and a 6.0-cm travel. This provides a frequency-tuning range of 1.0 MHz to compensate for beam loading, temperature effects, etc. A third port is used for vacuum pumping. Two 14-cm ports are provided for the beam.

The need for damping the higher-order modes (HOMS) in the cavity to suppress instabilities has been demonstrated on the 2.5-GeV Photon Factory storage ring.[7] Therefore, an antenna and a loop coupler with a band-stop filter for the fundamental frequency are placed in two 5-cm-diameter ports, 90° apart, in order to suppress higher-order modes.

Computations Using MAFIA and URMEL

Geometry of the storage ring cavity has been modeled using URMEL[8] and MAFIA.[9] Results[10] are in agreement within the capability of the tuner. MAFIA runs indicate the tuning range of the tuning plunger is ± 0.5 MHz. Additional computations indicate that the shunt impedance of some higher-order modes should be lowered (see Table V). We plan to shift modes that are coincident with exciting frequencies and to damp potentially troublesome modes.

Table V BUNCH STABILITY LIMITS

				One Cavity Worst Case		15 Cavities Best Case	
Mode	fr	Rs (MΩ)	Q(x10-4)	Growth Time T_r (ms)	Current Time I_T (mA)	Growth Time T_r (ms)	Current Time I_T (MA)
ME-1	540	3.35	4.2	5.32	23	157	751
EE-2	751	0.008	4.4	1607.5	6899	27155	116545
EE-3	923	1.20	10.5	21.1	91	644	2764
ME-2	948	0.464	4.4	22.1	95	240	1030
EE-4	1187	0.398	4.6	20.7	89	157	674
ME-3	1210	0.55	9.2	9.19	39	270	1159
EE-5	1326	0.018	12.5	412	1768	18360	78798
ME-4	1410	0.124	4.8	56.4	242	372	1597
EE-6	1505	1.0	8.5	6.58	28.2	107	459
ME-5	1545	0.013	9.2	494	2120	15350	65890

Calculations done for K_b = 20 bunches. The worst case is for a single cavity with R_S and Q having a frequency $f_r = (20\,p + s + V_s)\,f_0$.

The half integer case has 15 cavities with R_S (total) = 15 x R_S, and Q having a frequency $f_r = (20\,p + s \pm 1/2)f_0$ (i.e., midway between the closest revolution harmonic).

Source: S. Kramer and G. Nicholls, "Longitudinal EM Mode Calculation for APS RF Cavities and Their Impact on Coupled Bunch Stability," APS/IN/RF/89-2.

The center-to-center spacing of the cavities is λ. The waveguide lengths are adjusted to provide the right nominal phase with respect to the beam, and mechanically tunable phase-shifters are used for fine tuning of the cavity phase (= 0.5 to 1.0°).

Vacuum

Each cavity is pumped by a 400-ℓ/s ion pump. Remotely driven beam line valves are provided at each end of the straight section for isolation. One roughing system, including absorption pumps and turbopumps, is provided in each of the two rf power buildings. The base pressure of the cavity reaches 0.75 nTorr.

Radio Frequency Power System

A 1-MW klystron is used to drive five cavities. A block diagram for the five-cavity arrangement is shown in Fig. 2. From the klystron, the power is divided equally to the five cavities. The power is fed to the cavities in a waveguide directional coupler system as has been successfully applied at DESY on PETRA and HERA.[10]

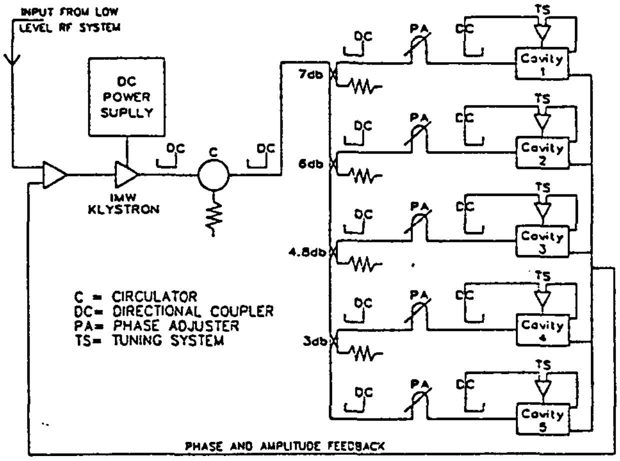

FIGURE 2 Schematic Diagram of Circuit Used to Split the Power from One 352-MHz, 1-MW Klystron and Distribute It to Five RF Cavities.

The power requirements for several different operating scenarios, including the normal operating condition, are listed in Table VI.

Table VI
POWER REQUIRED UNDER DIFFERENT OPERATING CONDITIONS

	7.0 GeV, 100 mA	7.0 GeV, 300 mA	7.5 GeV, 200 mA
Copper Loss (kW)	582	582	935
Power for Bending Magnet Synchrotron Radiation (kW)	545	1635	1436
Power for Insertion Device Synchrotron Radiation (full complement) (kW)	125	375	286
Power for Parasitic Mode Loss (kW)	20	60	40
Total Power into Storage Ring (kW)	1272	2652	2697
Storage Ring Voltage (MV)	9.5	9.5	12.04

Elevation and plan views of adjacent cavity, waveguide, and klystron systems in an rf power building are shown in Fig. 3.

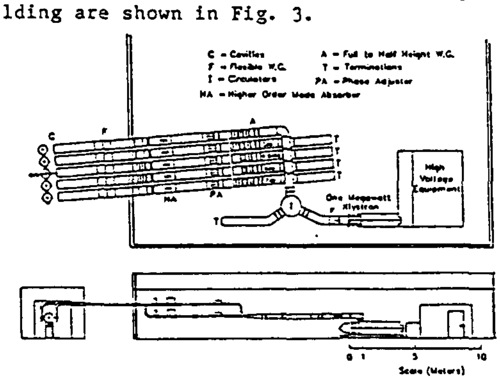

FIGURE 3 Elevation and Plan Views of Adjacent Cavity, Waveguide, and Klystron Systems in One of the RF Power Buildings.

The coupling loop on each cavity is adjustable to change the coupling constant from about 1.0 to 5. Since the circulators and klystron can safely handle large amounts of reflected power, the loop is normally set for optimum operation at the highest expected beam current during the operating period. This implies that the loop is overcoupled for lower currents, which will result in reflected power. The feedback loop that drives the tuning plunger works on only the reactive element of cavity input impedance. The klystrons with circulator can handle the reflected power from overcoupling at power levels below the maximum point in the designated operating cycle.

Klystrons

Either the Thomson-CSF TH2089 klystrons or the YK 1350 klystron available from Valvo will be used. A total of three 1-MW klystrons are required for 15 cavities.

Klystron Power Supplies

Klystron beam power is supplied by a 95-kV, 20-A multiphase rectifier with ± 0.5% ripple and regulation. A modulating anode supply is used to maximize efficiency. The klystron is fully protected by an electronic crowbar and arc detection circuitry. A prototype of this power supply system is now being fabricated for the rf test station.

Waveguides

The power from the 1-MW klystron is divided five ways. A three port circulator at the output of the klystron isolates the klystron. Phase adjustment and higher order mode absorbers are provided in the lines to each cavity. The harmonic voltages that are generated by the beam are absorbed by the HOM devices on the cavities.

Low-Level Radio Frequency System and Control

The frequency and phase of the storage ring rf system affect the beam position and energy. The main frequency source is stable to several parts in 10^{11} with phase continuity. The low-level rf system utilizes a digital synthesizer to control a phase-locked, voltage-controlled oscillator as the source. The output of this common frequency source is fed via phase-stable cables to each of the klystron amplifiers in the system. 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 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 klystron is adjusted to maintain the cavity voltage phase within ±1.0° (Fig. 3).

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

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