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1. Abstract

James F. Bridges
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439 USA

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The Advanced Photon Source (APS) is being built by Argonne National Laboratory (ANL) near Chicago. The APS is a 7-GeV positron storage ring from which x-ray beams of energies from a few keV to hundreds of keV are emitted as the positrons pass through ring bending magnets and also through special magnets called wigglers and undulators. The present schedule is to be operational in 1995.

The energy emitted from the positron beam as x-rays is replaced through a radio-frequency accelerating system operating at 352 MHz at a maximum power level of 3 MW.

The RF system will be described as well as several lower-power systems at frequencies of 0.8 MHz, 117 MHz and 2.8 GHz. The associated control electronics (phase shifters amplitude control, automatic tuning control, etc.) as well as the computer control architecture will also be described.

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2. Introduction

RF systems have been associated with particle accelerators since E. O. Lawrence invented the cyclotron in 1932 at the University of California at Berkeley. Two electrodes, called dees because of their D-like shape, were driven by a high powered, typically 20-40 kW, electron tube used as an oscillator. In the early sixties, frequency synthesizers were used to drive an amplifier chain with the output stage usually a large tetrode of about 100 kW output. The frequency band was about 7-20 MHz, depending on the ion accelerated.

Synchrotrons, having separated magnets and RF systems, overcame the limitations of cyclotrons and could accelerate protons to much higher energies. RF accelerating systems are distributed around the ring of magnets, have swept frequency operation and have output powers of several megawatts.

Electrons, because of their low mass, travel at the speed of light with very little energy, and so electron synchrotrons and storage rings operate at a fixed RF frequency. However, synchrotron light is emitted from the accelerated electrons in the range of infrared (10^{12} Hz) through the visible, ultraviolet and x-ray (2×10^{19} Hz) spectrum.

The energy lost as radiated light must be replaced by the RF System. For an intense light source even more power is needed. The APS storage ring RF power will be 3 M watt for a 300mA, 7 GeV stored beam. Since so much power is needed, the accelerating cavity design is optimized for high voltage with low power, i.e., the shunt impedance is maximized. Cavity optimization leads to higher frequencies, typically 500 MHz range, than previous (proton) accelerators. These higher frequencies are above the usual electron tube (tridoes & tetrodes) capabilities. Klystrons, usually used above 1 GHz, were developed to operate at 500 MHz, then 352 MHz and for CW operation.

For the low-level RF components, both amplitude and phase modulation circuitry is necessary. Maximizing the cavity impedance reduces the power for a given accelerating voltage. And for large beam currents needed for bright light sources, the beam current is larger than the source (Klystron amplifier) current. See Figure 2.1.

3. Project Description

The Advanced Photon Source (APS) at Argonne National Laboratory (ANL) is a high energy synchrotron x-ray source which provides at least a 100-mA beam of low-emittance, 7-GeV positrons capable of being stored for at least 10 hours. The

APS facility is specifically designed to optimize the use of insertion devices (IDs) because of the extremely high brilliance of the radiation produced by these devices. The lattice structure is a 40-sector Chasman-Green lattice which allows the stored beam to pass through insertion devices (undulators and wigglers) in the storage-ring. The photon beams produced in these straight sections contain fundamental x-ray energies up to 20 keV. In addition to these insertion device beams there are also available up to 35 photon beams from the bending magnets in the storage-ring. A layout of the Advanced Photon Source facility is shown in Figure 3-1.

The overall APS anatomy structure, the motion path of the positrons and the production of x-rays, are illustrated in Figure 3-2.

Even though the design energy of the stored positron beam is 7.0 GeV, the technical components of the facility are capable of producing stored beam energies up to 7.7 GeV. The design goals and specifications for the technical/facilities, are listed in Table 3-1. Reliability, stability and flexibility are emphasized in the designs of the components of the APS facility.

The Injector System is designed to fill the storage ring with a 7-GeV positron beam to at least 100 mA, in less than a minute (~ 50 s). The major components of the injector system are:

Linac

Low Energy Transport Line

Positron Accumulator Ring

Injector Synchrotron

High Energy Transport Line

A layout of the injector system is shown in Figure 3-3 and the design performance specifications are listed in Table 3-2.

The APS storage ring lattice is a Chasman-Green type containing dipole magnets for bending and quadrupole magnets for focusing the circulating positrons. Each magnet is individually powered. The ring contains 40 dispersion free straight sections, of which, 34 are available for insertion devices.

The storage ring receives full energy positrons from the injector and stores them as a low emittance beam of more than 100 mA for times greater than 10 hours. During the storage time, the beam is maintained at stable positions in the straight sections that contain insertion devices. A layout of one of the APS storage ring sectors is shown in Figure 3-4.

The function of the storage ring is to confine a 7 GeV positron beam to circulate stably around the ring. The very narrow and high intensity beam radiates synchrotron radiations of high brilliance and over a wide range of wave lengths. The general design performance parameters of the storage ring are given in Table 3-5.

4. X-ray Production

Fast-moving, charged particles, such as electrons traveling very close to the speed of light, radiate energy when an electromagnetic force causes their direction or speed to change. This radiation is emitted in the forward direction in a very intense, narrow beam. In synchrotrons, magnetic fields bend the particles' path, and photons ranging in energy from the infrared to the x-ray region of the electromagnetic spectrum are emitted. See Figure 4 - 1.

Through the use of wigglers and undulators, Argonne's Advanced Photon Source will produce x-ray beams in the energy range from 1 to 100 keV that are 10,000 times more brilliant than those available from bending magnets at Brookhaven National Laboratory's National Synchrotron Light Source (NSLS). Other synchrotron light sources depicted are proposed 1-2 GeV undulators at Lawrence Berkeley Laboratory, NSLS X-1 at Brookhaven, PEP undulator at Stanford University, and the SPEAR 54-pole wiggler at Stanford. See Figure 4-2.

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5. Linac

The Linac System consists of three major components:

1. The Electron Linac
2. The Tungsten Positron Production Target
3. The Positron Linac

The general design specifications of the linacs and their beam parameters are set by the requirements of the system and the acceptance of the Positron Accumulator Ring (PAR). A layout of the linac system is illustrated in Figure 5-1. The design performance specifications for the linac system are listed in Table 5-1.

The electron linac accelerates an electron beam to 200 MeV with 1.7 A output at a 60 Hz repetition rate. Each linac macropulse is 30 ns long and contains 50 nC of electrons by the process of multiple nuclear scattering.

Positrons are produced when the 200 MeV electron beam impinges on a 7 mm thick tungsten target. The positrons are focused by a solenoid field magnet and accelerated to 450 MeV in the positron linac. With each pulse of 50 nC of electrons, 0.42 nC of positrons are produced within the acceptance of the positron linac and 0.25 nC (1.5×10^9 positrons) are accelerated to 450 MeV.

The positron accelerating sections are constant-gradient, traveling-wave, exactly like the electron sections. Care has been taken to keep the positron beam diameter smaller than 13 mm by using a focusing system similar to those at DESY and LEP. This ensures that the positron beam is injected into the PAR with minimal loss. Linac parameters are listed in Table 5-2.

The option of injecting into the synchrotron 300 mA of electrons with energies up to 650 MeV can be done by withdrawing the positron target, rephasing the positron linac and reversing the focusing system.

In Figure 5-1, an Energy Compression System is shown as a set of devices forming a small curve in the positron beam line between the linac and PAR.

ENERGY GAIN CALCULATIONS

For	- Klystron Peak Power	35 MW
	- Frequency of Operation	2856 MHz
	- R.F. Pulse Length (Flat-top)	5 μs
	- Fill Time (waveguide) t_F	0.8 μs
	- SLED Energy Gain Factor (with 4 μs stored and then 180° phase reversal. $e^{\pm}$ injection between 4.75 μs + 4.8 μs)	1.78
	- SLED Power Gain	7.9 dB
	- Efficiency Factor (for 0.24 dB loss in 30' RFW + 7 flanges)	0.95

Figure 5-2 illustrates the planned power distribution for the e^- and e^+ linacs. Note that Klystrons II, IV, and V utilize SLED resonators.

For Klystrons I & III

Input Power = (35 MW-4MW) (.95) ≃ 29.5 MW
Note: (4MW to Buncher elements Klystron I)
(4MW to Energy Compression Klystron III) (if used)

Energy Gain = 58.8 MeV

For Klystron II, IV, and V (SLED):

$$\text{Input power into each section} = \frac{(35\text{ MW})(.95)}{4} = 8.3\text{ MW}$$

Energy Gain of each section = 222 MeV

The accelerating structures to be used will be of the SLAC type. Presently, RF windows will be employed to separate the RF power transmission waveguide vacuum from the accelerator structure vacuum.

To maintain the correct resonant frequency when RF power is applied, the phase of the structure will be measured and the temperature of the cooling water will be varied.

The accelerating structures are traveling wave constant gradient structures consisting of 86 cavities with an overall length of 3.05 m. The accelerating structures will be the same in both the electron and positron linacs. Figure 5-3 shows the preliminary drawing, and Table 5-3 lists the preliminary parameters for an accelerating structure.

The klystron modulators is a "line-type," using a capacitance-inductance network (pulse forming network, or PFN) constructed so as to simulate electrically a transmission line. A block diagram of the modulator is shown in Figure 5-4. The main pulse and charging circuits have been also drawn in schematic form. Table 5-4 lists the major parameters.

After each output pulse the PFN capacitors charge to approximately twice the DC power supply voltage due to the resonant charging characteristics of the charging transformer and the total PFN capacitance. The PFN capacitors retain this voltage level until the hydrogen thyratron tube is triggered. Once this occurs, the PFN capacitors discharge through the primary of the pulse transformer.

The value of the charge placed on the PFN can be regulated either by "Dequing systems" in conjunction with the silicon control rectifier (SCR) and the charging transformer, or by a tetrode vacuum tube switch between the DC power supply and the P.F.N.

6. Position Accumulator Ring (PAR) RF System

There are two RF systems in the PAR. One operates at 9.8 MHz, and the other at 117 MHz. Each 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 injector synchrotron during extraction.

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 parameters of the PAR RF System are given in Table 6-1.

6.1 Fundamental Frequency RF System

The cavity is a folded quarter-wavelength, coaxial re-entrant type that is capacitively loaded to resonate at a frequency of 9.8 MHz. Figure 6-1 shows a half section of the cavity, and the parameters are listed in Table 6-2.

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. No high-order-mode suppression is presently included, although ports are available and could be used for mode-damping circuits.

The power amplifier will be a commercially bought 5 to 10 kW amplifier. Two amplifiers can be used if this saves money and/or increases reliability. 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 (see Figure 6-2).

Pertinent parameters will be monitored, digitized, and interfaced to the Injector Control System for status monitoring.

Similarly, Control System commands will be interfaced to the various amplifiers for status control and to some extent for synchronization with linac and injector synchrotron.

6.2 Twelfth-Harmonic RF System

The twelfth-harmonic 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-MHzcavity 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 into 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 (Figure 6-3).

The power amplifier is located outside the shield wall, and power is fed to the cavity via a coaxial cable. This is a 2-kW amplifier (1600 watts for resistive loading). If beam and feedback control circuitry work well enough, the resistive loading may be removed. 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. Large induced voltages (224 kV) are avoided with programmed tuning. Figure 6-4 shows the control circuit for the cavity with both feedback signals from the cavity and feed-forward signals from a beam monitor. 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. The program can be a learning (adaptive) program to monitor the feedback error signals and adjust the program to minimize the errors. This correction can be done in several ways: over many PAR cycles, using only the last PAR cycle, or using a weighted running average. Using a correction signal improves the operation of the cavity; thus, for a given tolerance on cavity parameters, the feedback loop dynamic range and gain can be smaller.

The unloaded shunt impedance of the cavity is 2.0 MΩ and the maximum twelfth-harmonic beam current is 112 mA, so the maximum induced voltage without compensation due to the beam is 224 kV. The RF amplifier produces a 30-kV accelerating voltage, and the total current without compensation would cause the voltage to be 82.4° out of phase with the empty 117-MHz buckets and the 9.8-Hz bucket. Since only 222 W is needed to power the empty cavity, resistive loading is added to the cavity to lower the shunt impedance and reduce 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.

The 352-MHz frequency source is a synthesizer with direct digital synthesis (DDS) capability and resolution of 0.1 Hz. The DDS has phase continuity when switching frequencies so that no transient is present to disturb the stored beam. Switching is done by the control computer via a parallel bus. The correction signal is derived from the bunch signal in the storage ring. Two other synthesizers are referenced to the 352-MHz source, one for each of the PAR cavities (see Figure 6-5).

Since the rotation frequency, 9.8 MHz, of the PAR is not an exact multiple of 60 Hz, the linac is triggered by the PAR control system at a nominal 60-Hz rate. This ensures that the subsequent linac beam pulses are in the same place in the bucket as the first beam pulse.

Similarly, the PAR is synchronized to the synchrotron RF at extraction so the bunch is correctly placed with respect to previous bunches in the 352-MHz buckets.

7. Synchrotron RF System

The injector synchrotron RF voltage is produced 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 as the beam energy is increased. At extraction, the RF voltage is 10.4 MV, and the synchrotron radiation loss per turn is 6.38 MeV. The energy gain per turn is negligible compared with the synchrotron radiation losses. Table 7-1 lists the RF related parameters of the synchrotron. Figure 7-1 shows the physical layout with two cavities on each side of the synchrotron. The four cavities are driven by a single 1-MW klystron identical to those used for the storage ring.

The cavities for the 352-MHz injector synchrotron rf system are essentially copies of the LEP/PEP[2,3] five-cell, $\lambda/2$ resonant cavity. Each cell has a 10.0-cm diameter beam hole with a reentrant nose. The cell length is $\lambda/2$(426 mm). 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 five-cell structure is loopexcited in the center cell using a post-coupler from the WR2300 waveguide. Tuners are located in the two cells adjacent to the center cell. Vacuum separation between the waveguide and the cavity is 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. See Figure 7-2 and Table 7-2.

The cavity is fitted with two 220 l/s ion pumps on the two outermost cells. After the cavity has been RF processed to full power, this amount of pumping capacity should maintain the beam path volume of the cavity at 10^{-10} Torr or better.

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. A circulator protects the klystron from reflected power. Static phase shifters are used to adjust the phase to the four cavities.

The klystron which is used for the RF power amplifier is manufactured by two European companies and were developed by CERN in Geneva. A photo of the klystron is shown in figure 7-3. The klystron operates with a negative voltage on the cathode in the range of 100 kV. The body and all accessible outer surfaces of the klystron are at ground potential. The RF drive power is applied to the first klystron cavity (nearest the cathode) and the output power is coupled out of the last klystron cavity, then to the waveguide which is atop the klystron.

The klystron power supply must power all the elements of the klystron; these include the cathode heater power, the modulating anode power, the focusing magnet power, and the klystron beam power. The power supply system also includes equipment and personnel protective interlocks.

The RF system is under active computer control and is continuously monitored by the main control computer. The five cells of the cavity each have field monitors. The monitors are added in phase and the resultant signal is compared with a digital phase meter to the driving signal. The digital phase information goes to the control computer, the computer adds an offset to maintain the proper voltage amplitude and phase. The computer then controls the two tuners of each cavity to keep the cavity tuned in the presence or absence of beam loading. The monitoring system also records the cavity temperature, cavity power, klystron power supply and warns of improper operating conditions.

8. Storage Ring RF System

The RF system must generate 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 vacuum window and (b) 800-kV peak voltage per cavity. The nominal frequency of operation for the storage ring rf system is 352 MHz.

The RF system uses 15 single-cell cavities. These are the same type of cavities used at the Photon Factory in Tsukuba[4] and the SRS in Daresbury.[5] Three 1-MW klystrons power the cavities. Each klystron drives five cavities. Each group of five cavities is located in a 6-m straight section. A third-harmonic cavity, operating at 1056 MHz and 1.8 MV, is located in the 30th straight section after injection. The RF parameters are listed in Table 8-1, and the parameters of the beam and RF system in Table 8-2.

Figure 8-1 shows the cross section and dimensions of the single-cell cavity used for the storage ring. Calculations with the computer program URMEL[6] and 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.

Each storage ring cavity has four 14-cm- and two 12-cm-diameter ports. One port is used for the coupling loop which is post-excited from a WR2300 waveguide (can be adjusted) for coupling-coefficient. The post is vacuum-sealed from the air-filler waveguide by a cylindrical ceramic window. The second port is fitted with a tuner of the plunger type (Figure 8-2) and has an 11.5-cm diameter and a ± 6.0-cm travel as shown in the graph in Figure 8-3. This results in a frequency-tuning range of 1.0 MHz to compensate for beam loading and temperature effects. A third port is used for vacuum pumping. Two 14-cm ports are the beam ports.

An antenna and a loop coupler with a band-stop filter for the fundamental frequency are placed in two 50 cm-diameter ports, 90 apart, in order to suppress high-order modes. A list of the lowest higher-order modes with their undamped shunt impedances and Q values calculated with URMEL is given in Table 8-3. The frequencies agree closely with values scaled from measurements on the 500-MHz cavities at the Photon Factory; hybrid modes are expected at 482.3, 580.5, 749.6, 796.5 and 871.5 MHz. These modes cannot be verified with any of the cavity computer programs, since these programs do not calculate hybrid modes. The antenna- and loop-damping couplers are successful in eliminating the effects of the higher-order longitudinal and transverse modes on the stored beam.

The center-to-center spacing of the cavities is 0.852 m. The waveguide lengths are adjusted to phase the cavities with respect to the beam, and mechanically tunable phase-shifters are used for fine tuning of the cavity phase (≃ 1.0 degree).

A 1-MW klystron drives five cavities. A block diagram for the five-cavity arrangement is shown in Figure 8-4. 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.

Elevation and plan views of adjacent cavity,, waveguide, and klystron systems in an RF power building are shown in Figure 8-5.

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.

Table 8-4 lists the operating parameters for the Thomson-CSF TH2089 klystrons. The YK 1350 klystron available from Phillips-Valvo has similar characteristics, and either tube could be used. A total of three 1-MW klystrons are required for 15 cavities.

The RF power delivered to the beam via the cavities can be much larger than that used to excite the cavity to the required voltage. The highest coupling constant between drive loop and the cavity alone, β, required is about 4.5. The cavity coupling will be adjusted to give a matched condition at the circulating current.

It is necessary to compensate for the reactive component of beam loading. This is done prior to beam injection by detuning to comply with the requirement of the Robinson instability criterion.[7] For stability,

$$[1/(1+\beta)]\,(P_b/P_c) < 1.$$

The required amount of detuning from the no-beam condition to the fully loaded condition is

$$\Delta f = -\,(f_{rf}/2Q_o) \times (P_b/P_c) \times \cot\,(\text{phase angle})$$

$$= (352 \times 10^6/2 \times 40 \times 10^3) \times (176/39) \times \cot\,(51.2) = -15.91\ \text{kHz.}$$

(Note that beampower is 4.5 times the cavity power.)

This detuning coverage can easily be handled by the tuning system, which has a range of 1 MHz. Detuning requires additional power. 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 controls. The low-level loops are fast enough for this application.

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.

9. Acknowledgements

The RF systems design were designed by the following people:

Robert Kustom

George Mavrogenes

James Bridges

Gilbert Nicholls

William Wesolowski

Conceptual design[8] was complete in 1987 and detailed designs are being done until 1993. Both a Linac Test Stand and a 352 MHz RF Test Stand are being built. Two views of the RF Test Stand are shown in Figures 9-1 and 9-2. The Linac Test Stand will be built in early 1991, for testing the electron guns and one three-meter section of accelerating waveguide.

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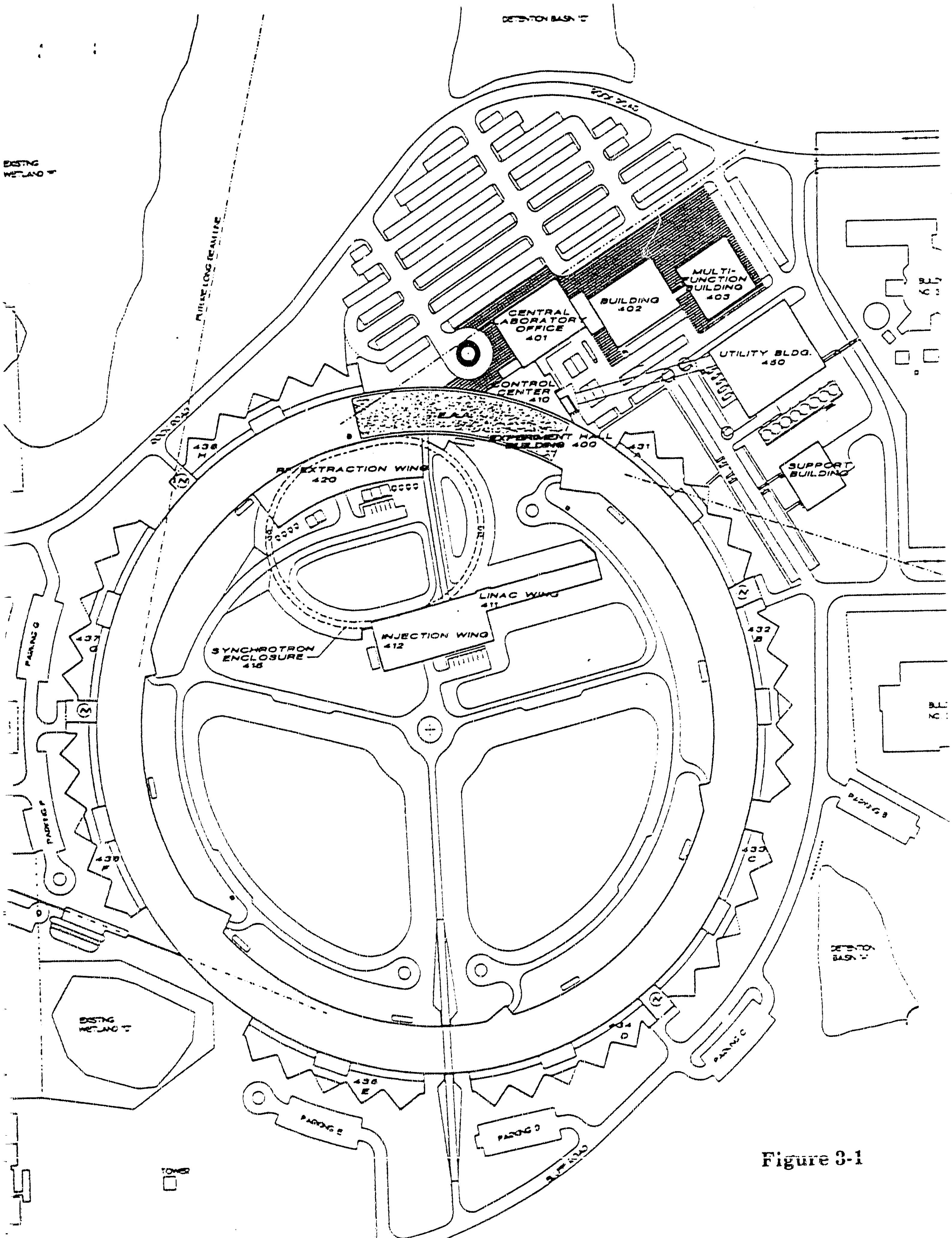


CENTRAL LABORATORY OFFICE 401
BUILDING 402
MULTI-FUNCTION BUILDING 403
UTILITY BLDG. 450
CONTROL CENTER 410
EXPERIMENT HALL BUILDING 400
SUPPORT BUILDING
EXTRACTION WING 420
LINAC WING 411
INJECTION WING 412
SYNCHROTRON ENCLOSURE 416
436 H
431 A
437 G
432 B
433 C
436 E
EXISTING WETLAND
DETENTION BASIN
PARKING G
PARKING F
PARKING E
PARKING D
PARKING C
PARKING B
TOWER

Figure 3-1

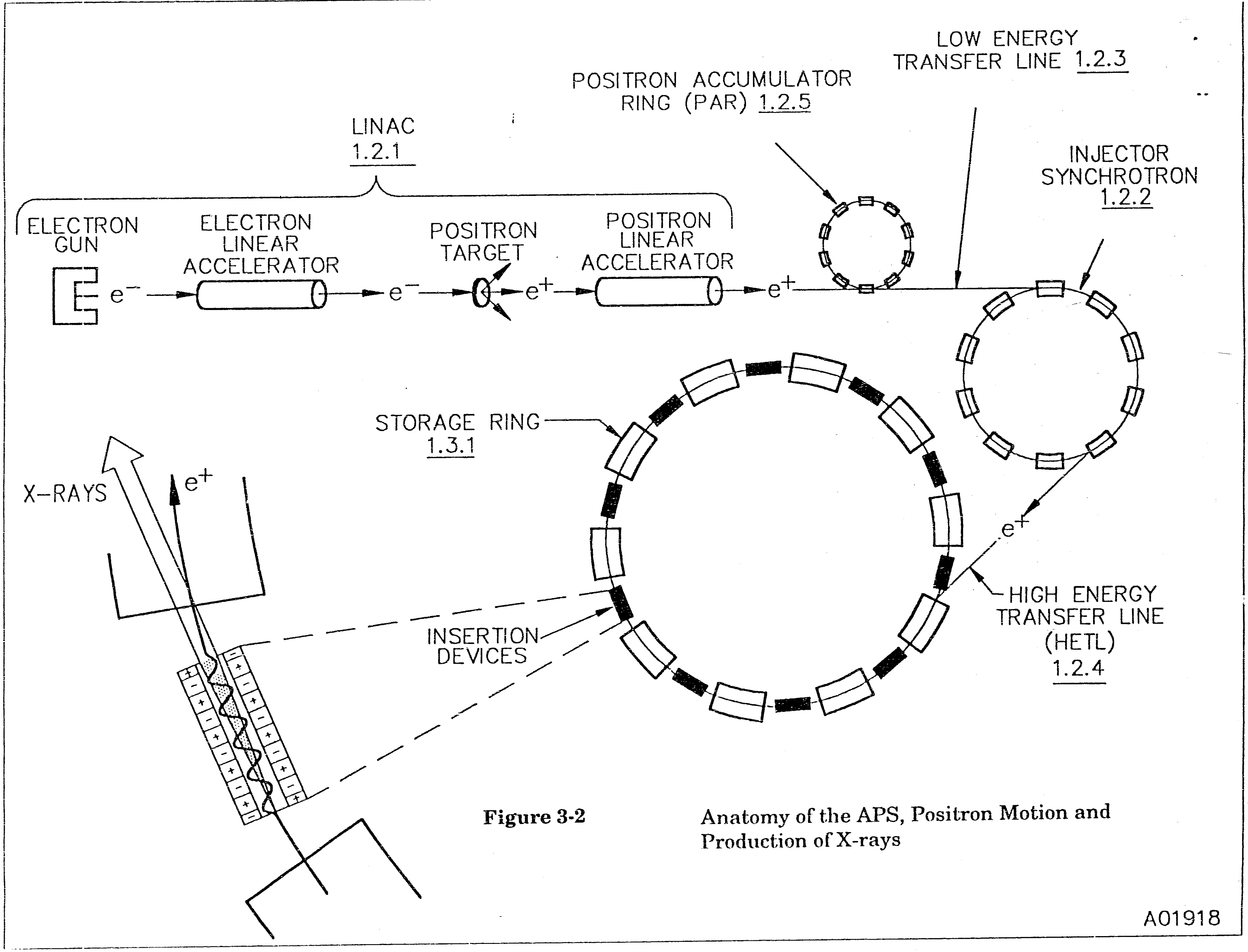


Figure 3-2 Anatomy of the APS, Positron Motion and Production of X-rays

Table 3-1

Design Goals and Specifications for the

Technical/Facilities of the Advanced Photon Source

DESIGN PARAMETER GOALS	COMMISSIONING	
Linac Energy (e^-)	200	MeV
Linac Energy (e^+)	450	MeV
Synchrotron Energy	7	GeV
Storage Ring Energy	7	GeV
Storage Ring Beam Current	20	mA
Beam Lifetime	>3	h
Undulator Fundamental Energy Range (Nominal)	4-14	keV

DESIGN PARAMETER	OPERATIONAL GOALS	
Beam Energy	7	GeV
Beam Current	100	mA
Beam Lifetime	>10	h
Number of Bunches	1-60	
Bunch Duration	50-100	ps
Horizontal Emittance	10	nm·rad
Number of Straight Sections	40	
Straight Section Length (for IDs)	5	m

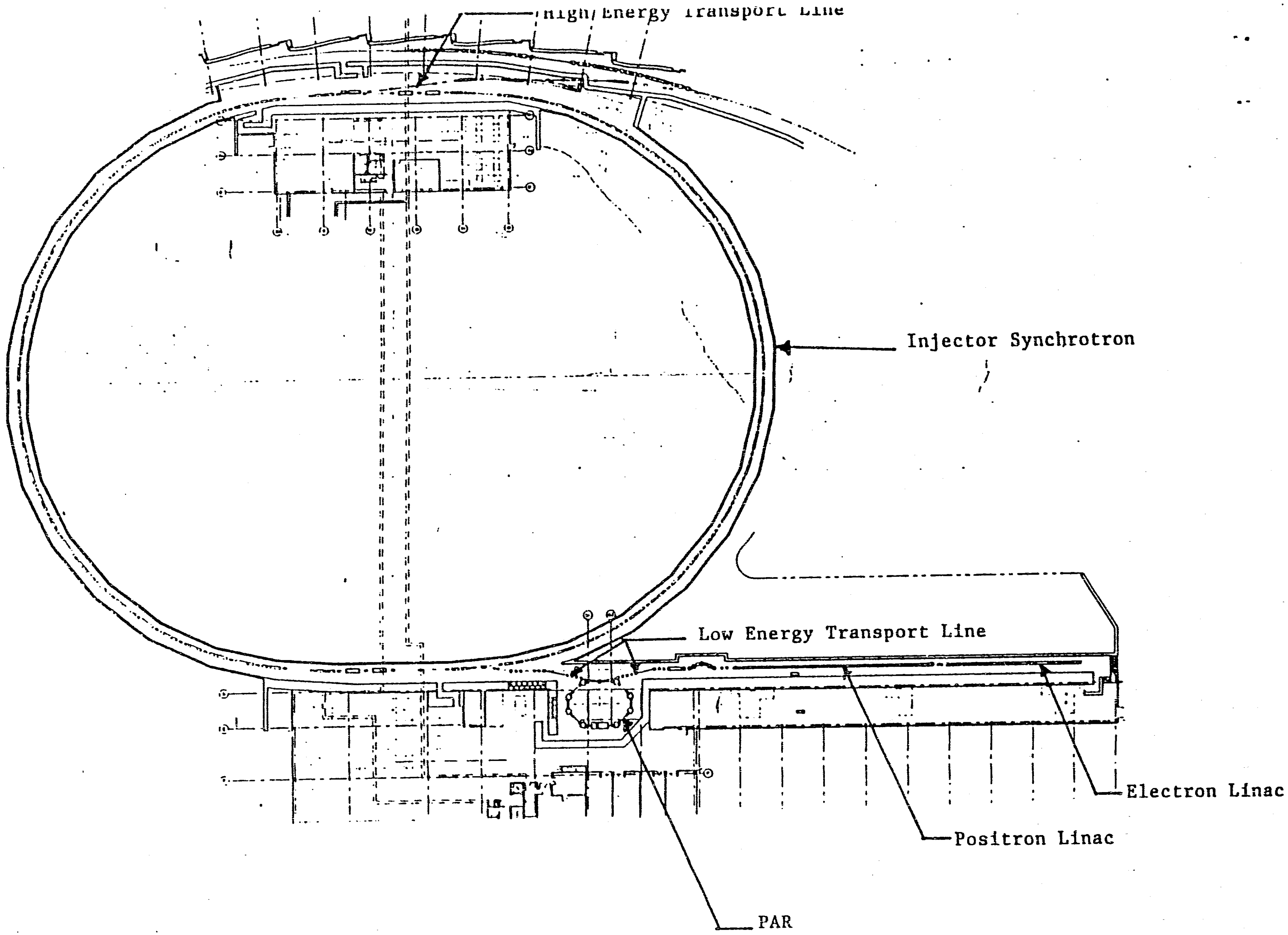


Figure 3-3 Layout of the APS Injector System

Table 3.2

Design Performance Specifications for the Injector System

Electron Linac Output Energy	200	MeV
Positron Linac Output Energy	450	MeV
Linac Repetition Rate	60	Hz
Injector Synchrotron Output Energy	7	GeV
Synchrotron Rep. Rate	2	Hz

Table 5-1

Design Performance Specifications for the Linac System

Electron Linac		
Output Energy	>200	MeV
Output Current	1.7	A @ 30 ns
Repetition Rate	60	Hz; 24 contiguous 16.7 ms apart every 1/2 s
Spot Size	< 3	mm diameter
Longitudinal Bunch	< 15°	
Emittance (95th Percentile)	< 1.2	mm-mrad at 200 MeV
Energy Spread ΔE/E*	< ±8%	
Positron Linac		
Input Energy	8	MeV
Output Energy	450	MeV
Energy Spread, $\frac{\Delta E^*}{E}$ (95th percentile)	< ± 0.01	
Transmission Efficiency	≥ 60%	
Emittance (95th percentile)	6.6	mm-mrad

*The energy spread and the emittance are significant only to the extent that a 3 mm diameter beam spot size is not achieved at the positron converter.

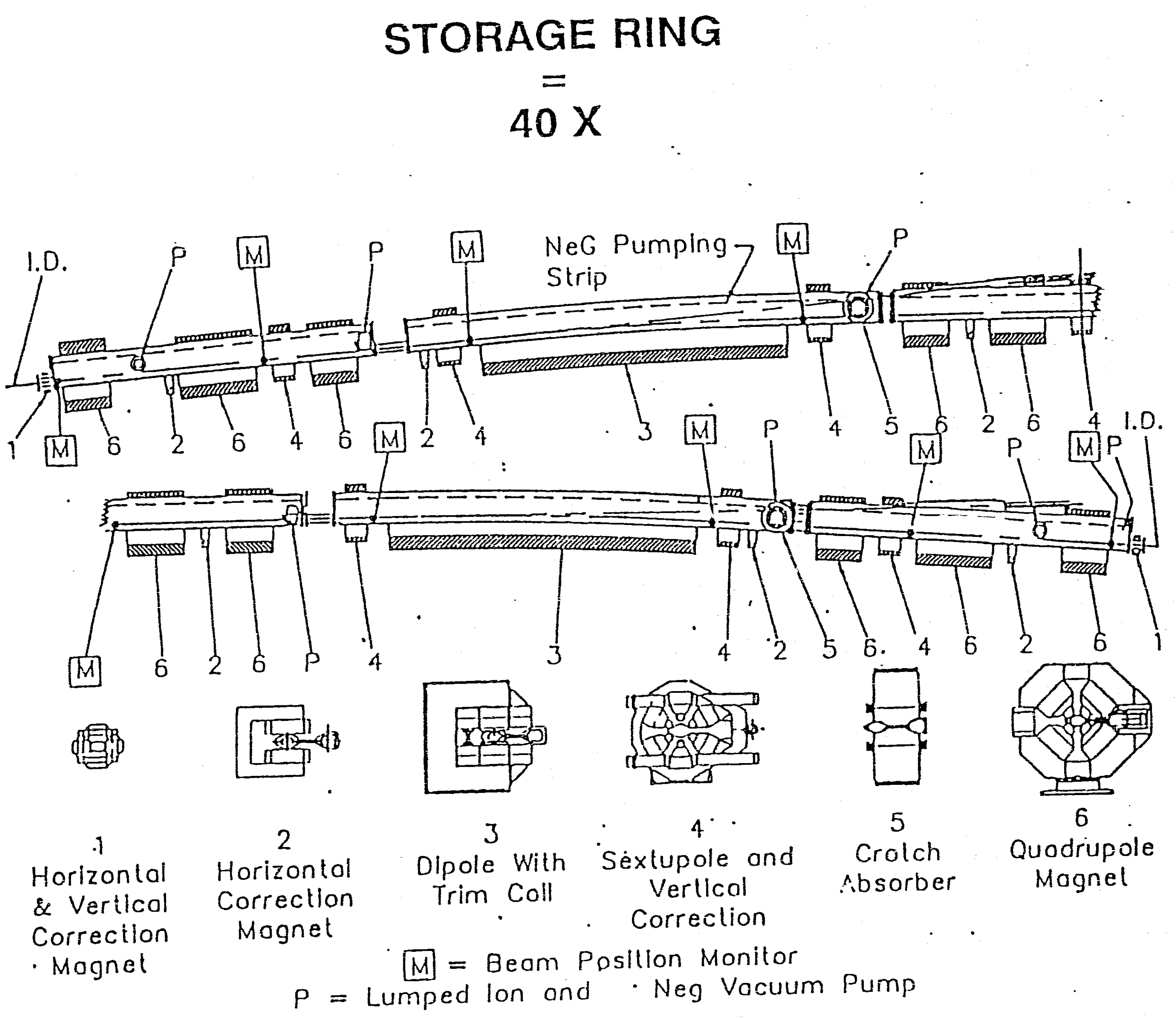


Figure 3-4 Layout of an APS Storage Ring Sector

Table 3-3

Design Performance Goals and Parameters for the Storage Ring

Nominal energy	7.0	GeV
Nominal circulating current, multibunch	100	mA
Nominal number of stored positrons, multibunch	2.3×10^{12}	
Maximum circulating current, multibunch	300	mA
Maximum number of stored positrons, multibunch	6.9×10^{12}	
Maximum circulating current, single bunch	5	mA
Number of stored positrons, single bunch	1.2×10^{12}	
Harmonic number	$2^4 \times 3^4$	= 1296
Natural emittance	8.2×10^{-9}	m-rad
Natural energy spread, rms	9.6×10^{-4}	
Energy spread, rms, at max. bunch current	2.9×10^{-3}	
Bunch length, rms, natural	5.3	mm
Bunch length, fwhm, natural	27.5	ps
Bunch length, fwhm, maximum bunch current	72.5	ps
Max energy	7.7	GeV
Beam lifetime, mean-life		
Gas scat., 8-mm vert. gap,		
1 nTorr 75% H2 & 25% CO	76	h
Touschek, maximum bunch current	190	h
Filling rate	4.3×10^{10}	e^+/s
Filling time		
Multibunch, to 100 mA	0.9	min
Single bunch, per 5 mA bunch	2.7	s

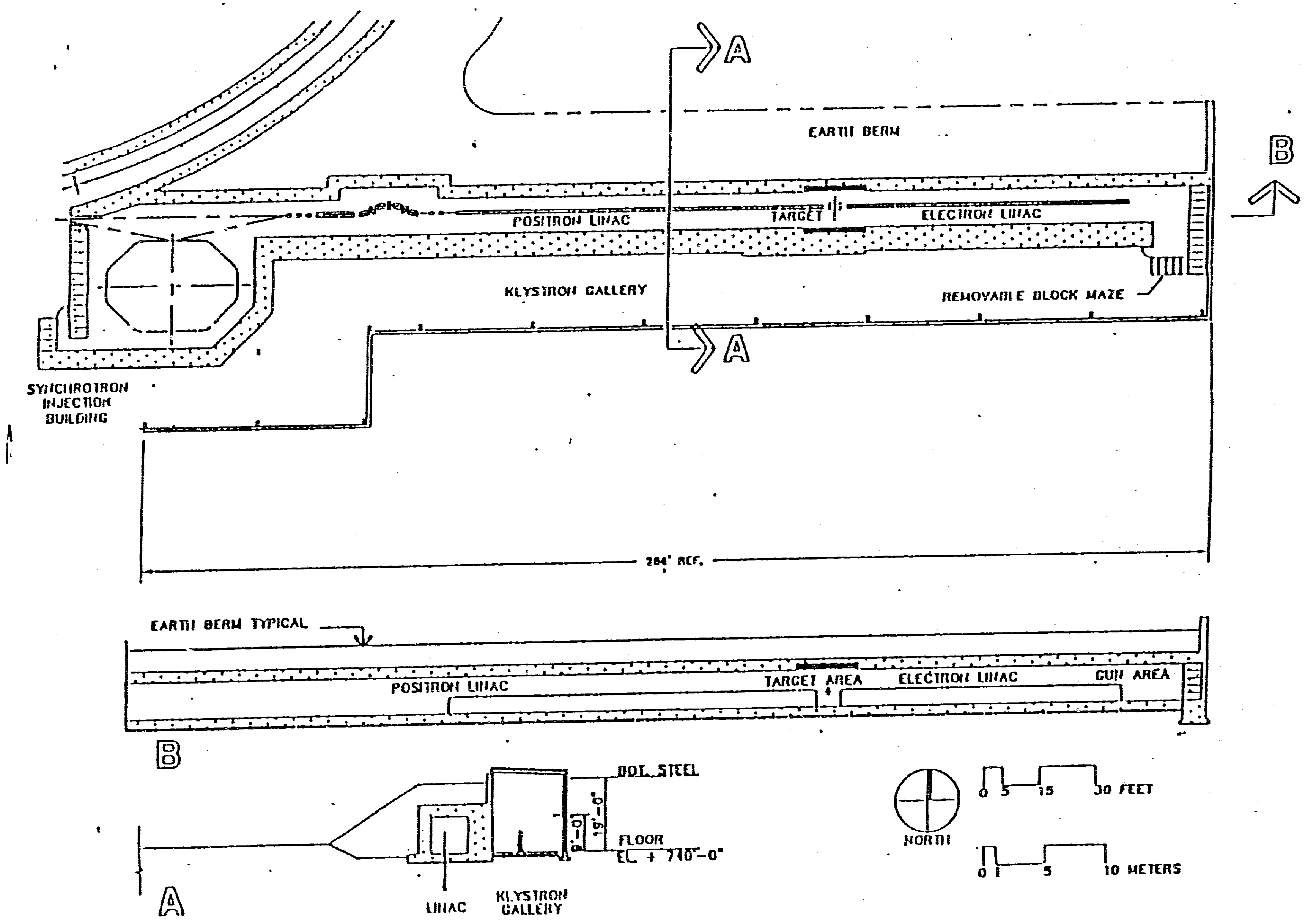


Figure 3-5 Layout of the APS Linac Building

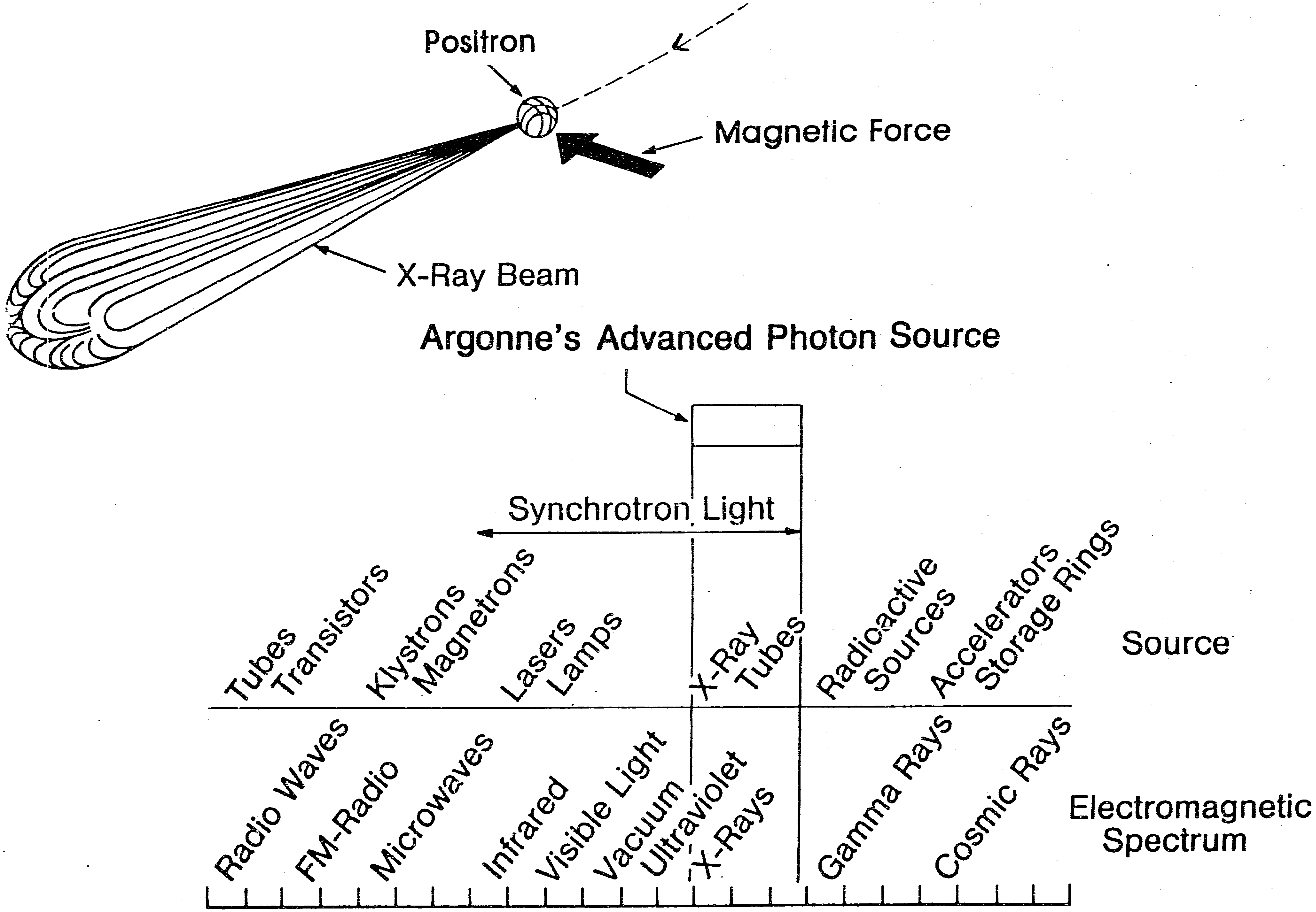
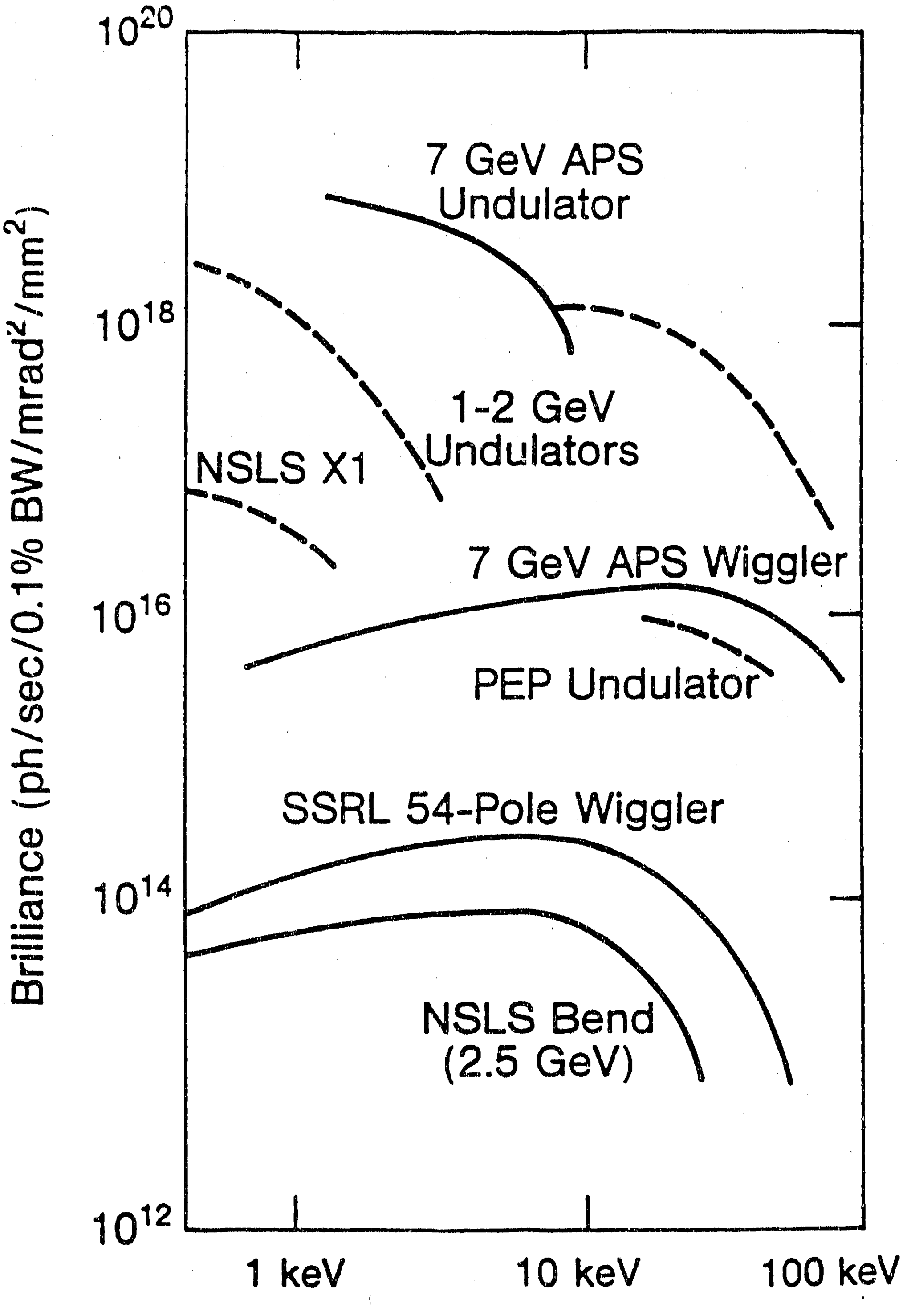

Positron
Magnetic Force
X-Ray Beam
Argonne's Advanced Photon Source
Synchrotron Light
Tubes
Transistors
Klystrons
Magnetrons
Lasers
Lamps
X-Ray
Tubes
Radioactive
Sources
Accelerators
Storage Rings
Source
Radio Waves
FM-Radio
Microwaves
Infrared
Visible Light
Vacuum
Ultraviolet
X-Rays
Gamma Rays
Cosmic Rays
Electromagnetic
Spectrum

Figure 4-1



10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
Brilliance (ph/sec/0.1% BW/mrad^2/mm^2)
7 GeV APS
Undulator
1-2 GeV
Undulators
NSLS X1
7 GeV APS Wiggler
PEP Undulator
SSRL 54-Pole Wiggler
NSLS Bend
(2.5 GeV)
1 keV
10 keV
100 keV

Figure 4-2

Table 5-2

Parameters of the Linacs

a.	**General**		
	Linac e^-	200	MeV
	Linac e^+	450	MeV
	Frequency	2.856	GHz
	Total number of TW accelerating sections	14	
	Number of klystrons with SLEDS	3	
	Number of klystrons without SLEDS	2	
b.	**Linac e^-**		
	Gun voltage	100	kV
	Prebuncher I, type SW, single-gap re-entrant cavity		
	Buncher, TW, beta = .75 6 cavities long		
	Number of TW accelerating sections	5	
	Pulse repetition rate	60	Hz (24 contiguous 16.7 ms apart every 1/2 s)
	Beam pulse length	30.0	ns
	Pulse current (output)	1.7	A
	Emittance, 95 percentile	< 1.2	mm-rad
	Bunch length (90% of particles)	15°	
	Energy spread ($\Delta E/E$)	± 0.08	
c.	**Target**		
	Target material	Tungsten	
	Target thickness, (2Xo)	7	mm
	e^- beam diameter on target	< 3	mm
	Average incident power	500.0	W
	Pulsed solenoidal field	1.5	T

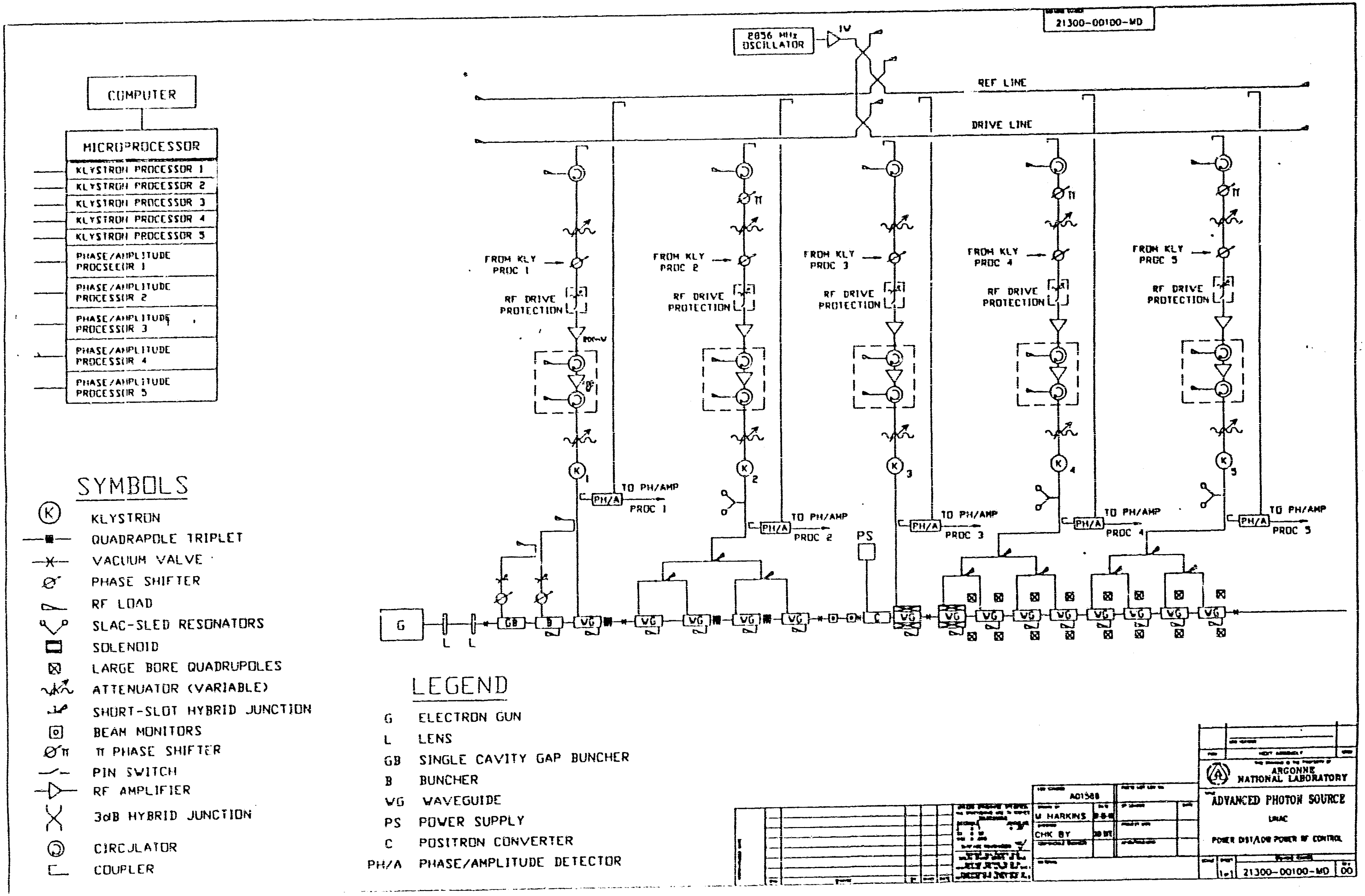
Table 5-2 (Cont.)

Conversion efficiency e^+/e^-	0.0083	
Mean energy of positrons from target for 200 MeV incident electrons	8	MeV

d. Linac e^+

Linac output energy	450	MeV
Linac output current	8	mA
Emittance, 95th percentile	6.6	mm-mrad
Energy spread, 95th percentile	± 0.01	
Transmission efficiency	≥ 60%	
Number of TW sections	9	
Overall e^+/e^- conversion efficiency	0.005	

Figure 5-2



21300-00100-MD
2856 MHz OSCILLATOR
1V
REF LINE
DRIVE LINE
COMPUTER
MICROPROCESSOR
KLYSTRON PROCESSOR 1
KLYSTRON PROCESSOR 2
KLYSTRON PROCESSOR 3
KLYSTRON PROCESSOR 4
KLYSTRON PROCESSOR 5
PHASE/AMPLITUDE PROCSECOR 1
PHASE/AMPLITUDE PROCESSOR 2
PHASE/AMPLITUDE PROCESSOR 3
PHASE/AMPLITUDE PROCESSOR 4
PHASE/AMPLITUDE PROCESSOR 5
FROM KLY PROC 1
FROM KLY PROC 2
FROM KLY PROC 3
FROM KLY PROC 4
FROM KLY PROC 5
RF DRIVE PROTECTION
TO PH/AMP PROC 1
TO PH/AMP PROC 2
TO PH/AMP PROC 3
TO PH/AMP PROC 4
TO PH/AMP PROC 5
PH/A
PS
G
L
GB
B
VG
C
SYMBOLS
KLYSTRON
QUADRAPOLE TRIPLET
VACUUM VALVE
PHASE SHIFTER
RF LOAD
SLAC-SLED RESONATORS
SOLENOID
LARGE BORE QUADRUPOLES
ATTENUATOR (VARIABLE)
SHORT-SLOT HYBRID JUNCTION
BEAM MONITORS
π PHASE SHIFTER
PIN SWITCH
RF AMPLIFIER
3dB HYBRID JUNCTION
CIRCULATOR
COUPLER
LEGEND
G ELECTRON GUN
L LENS
GB SINGLE CAVITY GAP BUNCHER
B BUNCHER
VG WAVEGUIDE
PS POWER SUPPLY
C POSITRON CONVERTER
PH/A PHASE/AMPLITUDE DETECTOR
ARGONNE NATIONAL LABORATORY
ADVANCED PHOTON SOURCE
LINAC
POWER DIST/LOW POWER RF CONTROL
A01588
M HARKINS
CHK BY
21300-00100-MD
00

Table 5-3

Accelerating Structures
(SLAC Type Accelerating Structures)

Type of Construction	Constant Gradient	
Operating Frequency	2856	MHz
Number of Sections	5 e^- ; 9 e^+	
Overall Length of Sections, l	305	cm
Number of Cavities Per Section	86	
Phase Shift	$\frac{2\pi}{3}$	
Field Attenuation, τ	.57	Np
Shunt Impedance for Fundamental r_o	52 - 60	MΩ/m
Q	13,000	
Filling Time $t_F = l/v_g$	$.83 \times 10^{-6}$	s
Waveguide Diameter, 2b	8.3461 - 8.1793	cm
Iris Aperture Diameter, 2a	2.622 - 1.9235	cm
Disc Thickness	.5842	cm
Klystron Peak Output Power Rating	35	MW

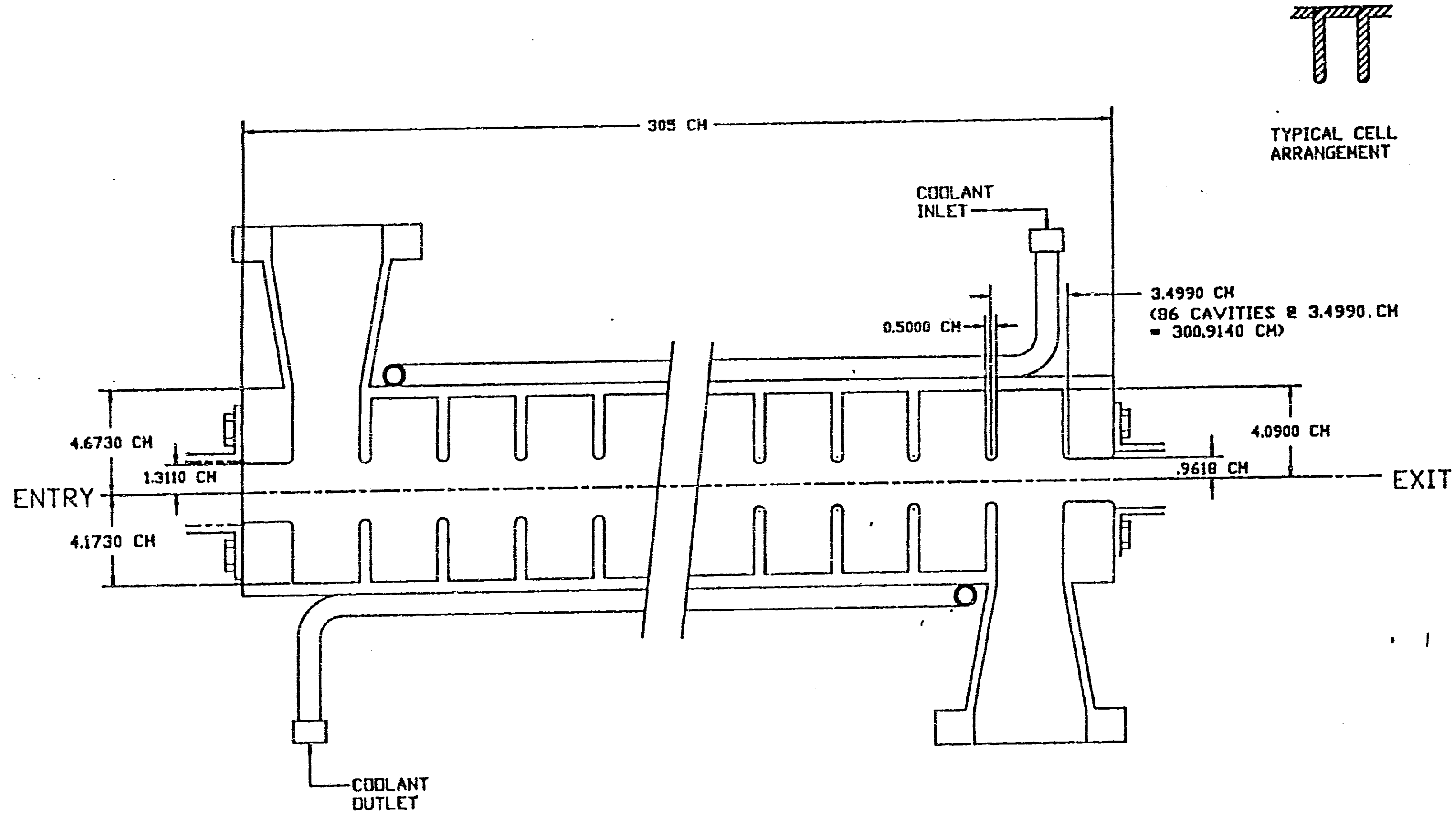


Figure 5-3 Constant Gradient T.W. Accelerating Structures (SLAC type)

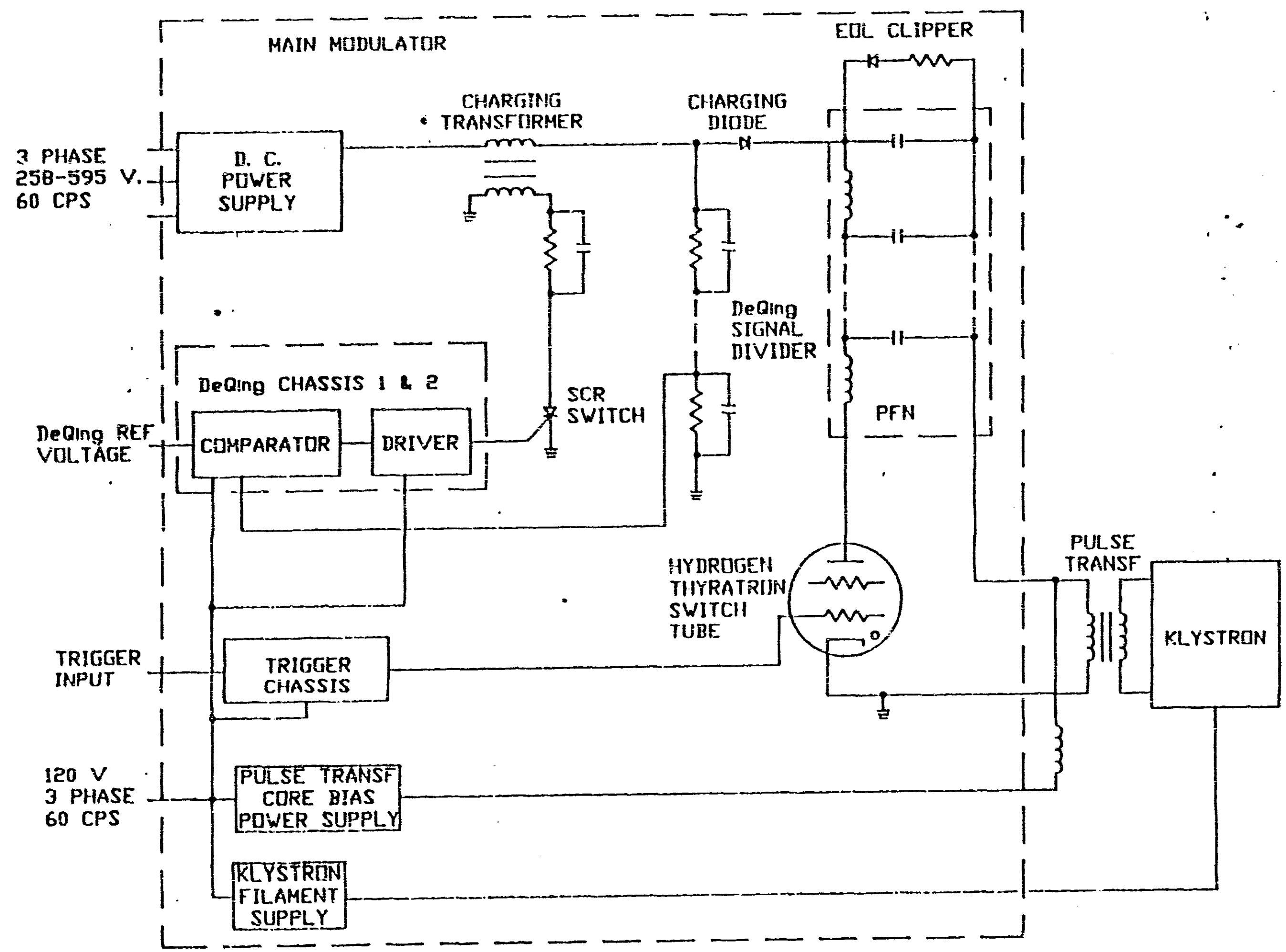


Figure 5-4 Modulator Block Diagram

Table 5-4

Power Supply Parameters

Peak Power Output	100 MW
Average Output Power	36 KW arc
Output Pulse Voltage Peak	315 kV
Output Pulse Current, Peak	315 A
HV Pulse Flat-top Width	5 μs
Voltage Rise-time into klystron load	700 ns
Pulse Repetition Rate	60 Hz

Table 6-1

Parameters for PAR RF Systems

RF Systems		
System I		
Frequency, f	9.77584	MHz
Harmonic number, h	1	
Peak Voltage, V	40	kV
Synchrotron frequency, f_s	19.0	kHz
Natural bunch length (damped)	0.92	ns
System II		
Frequency, f	117.3101	MHz
Harmonic number, h	12	
Peak voltage, V	30	kV
Synchrotron frequency, f_s	60.2*	kHz
Natural bunch length (damped)	0.29*	ns

*System I and II both ON

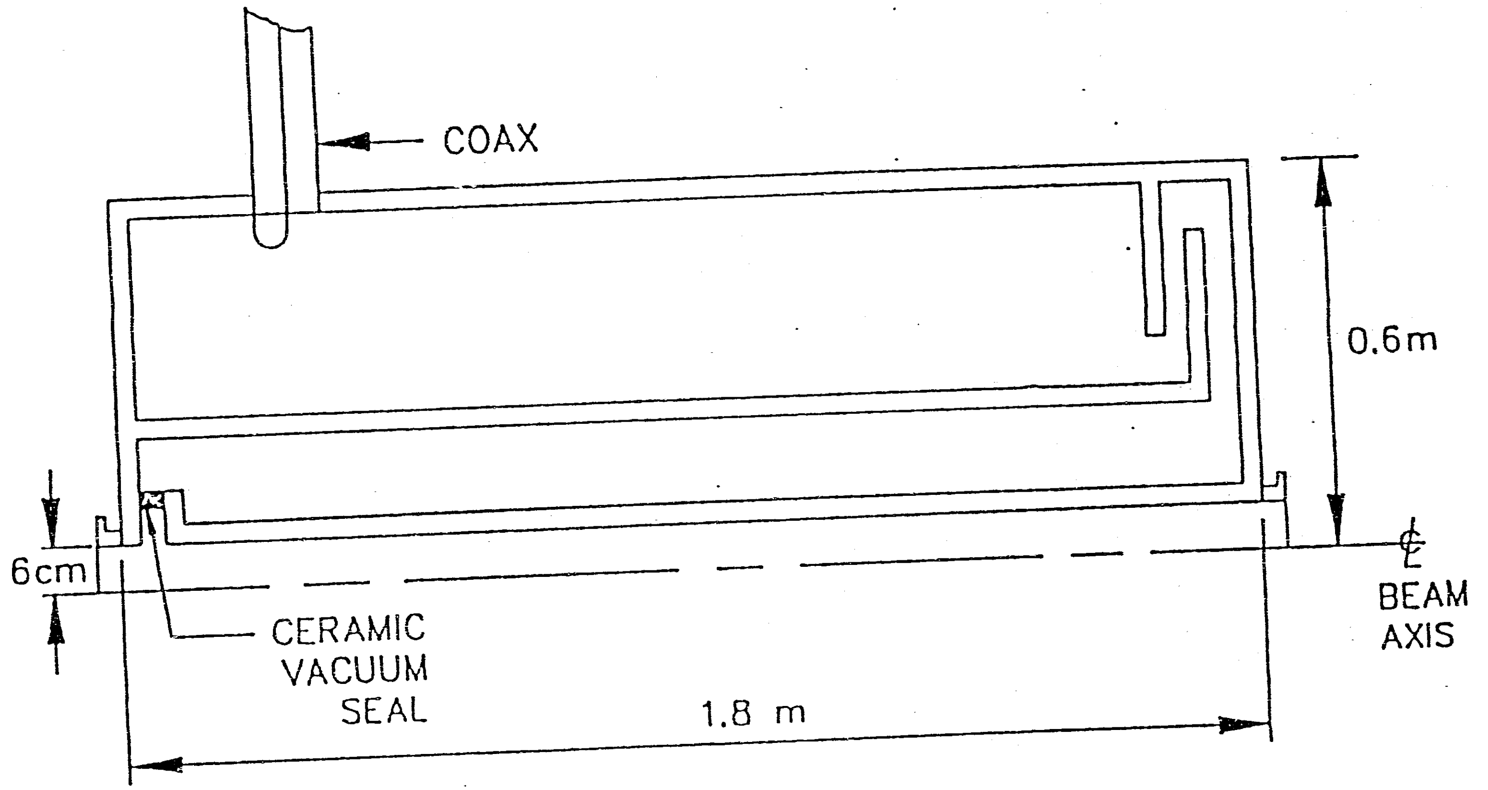


Figure 6-1 **Schematic of First Harmonic (9.8-MHz) Cavity, Half Section**

Table 6-2

PAR Cavity Parameters

Parameter	First-Harmonic	Twelfth-Harmonic
f (MHz)	9.7758	117.309
V (kV)	40	30
Type	$\lambda/4$, loaded	$\lambda/2$
Length (m)	1.8	0.9
Z_o (Ω)	50	50
Power (kW)	4.70	0.222
R_s (kΩ)	170	2020
Q	7,630	25,300
τ [= $2Q/\omega$] (μs)	248	68

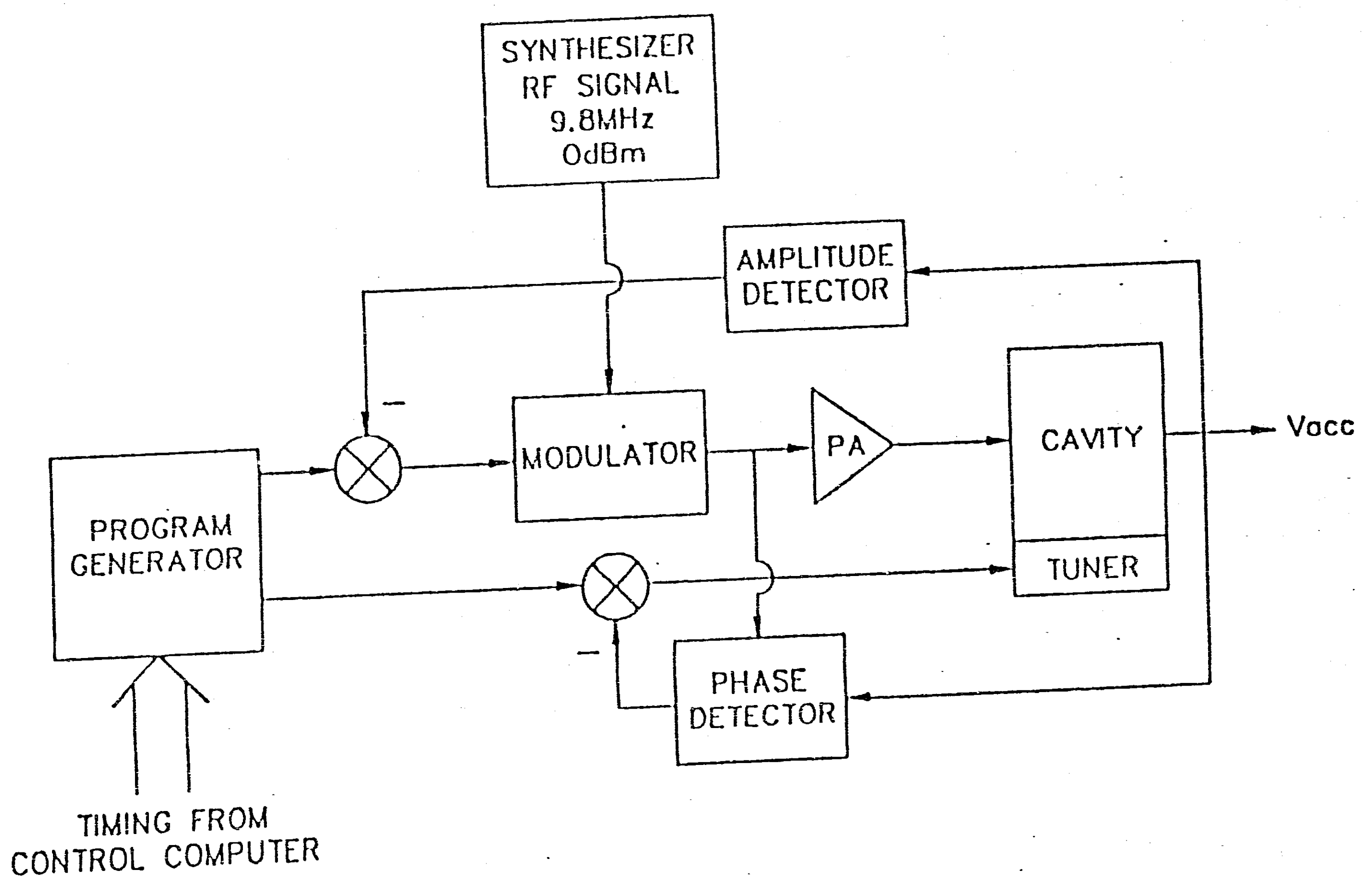


Figure 6-2 9.8-MHz RF System Block Diagram Showing Program Generator

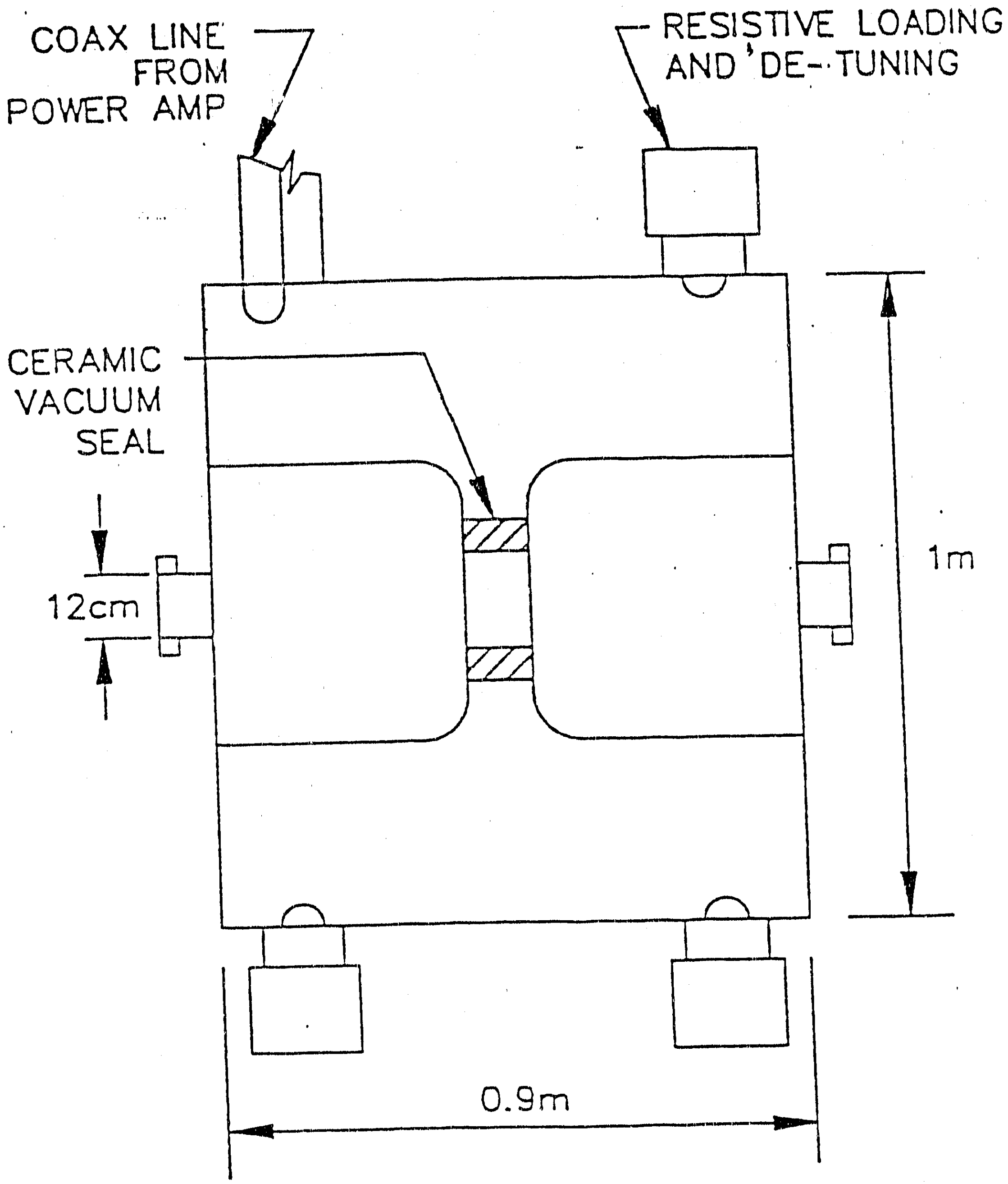


Figure 6-3 Schematic of Twelfth Harmonic (117-MHz) Cavity

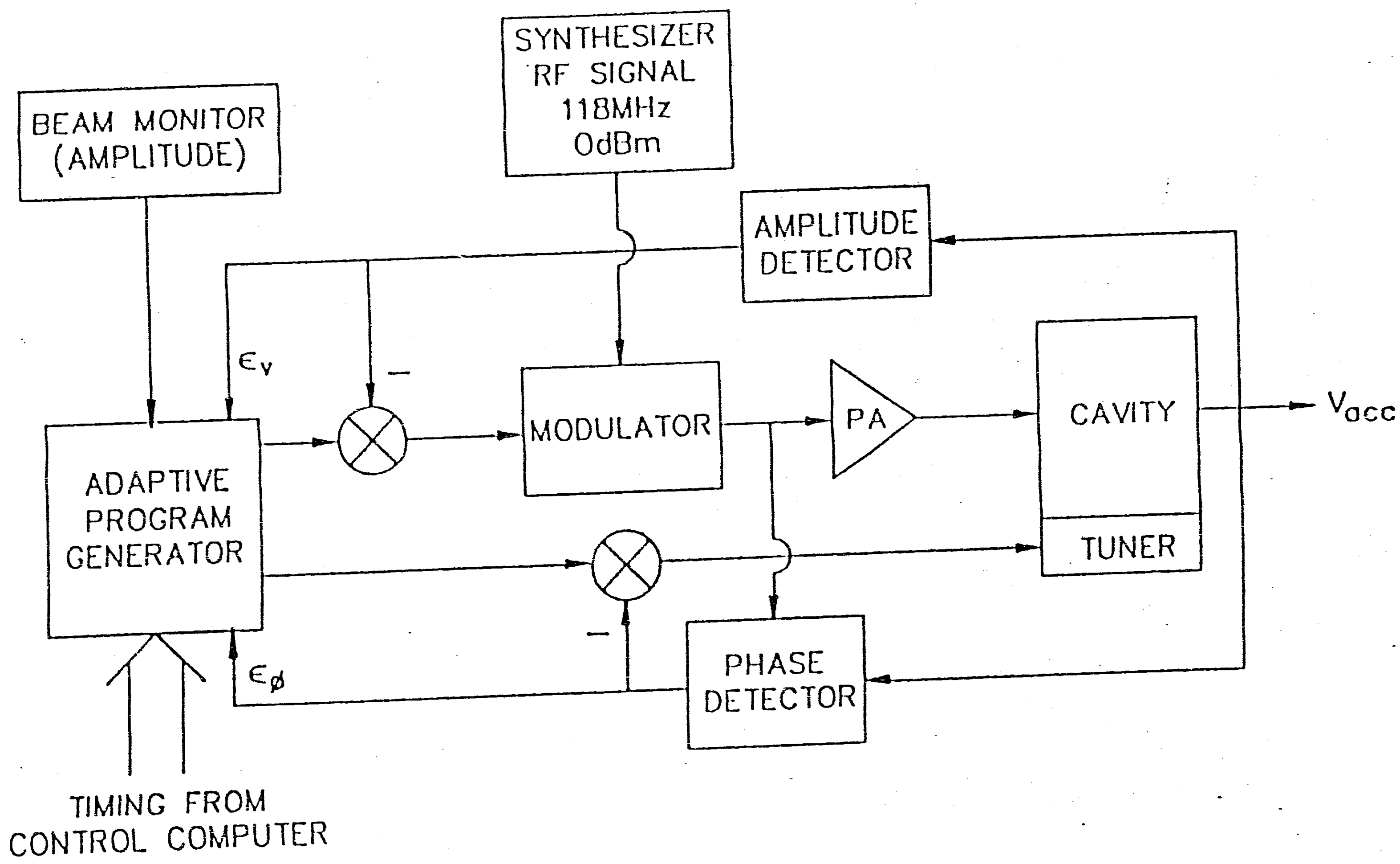


Figure 6-4 Twelfth Harmonic (117-MHz) RF System Block Diagram

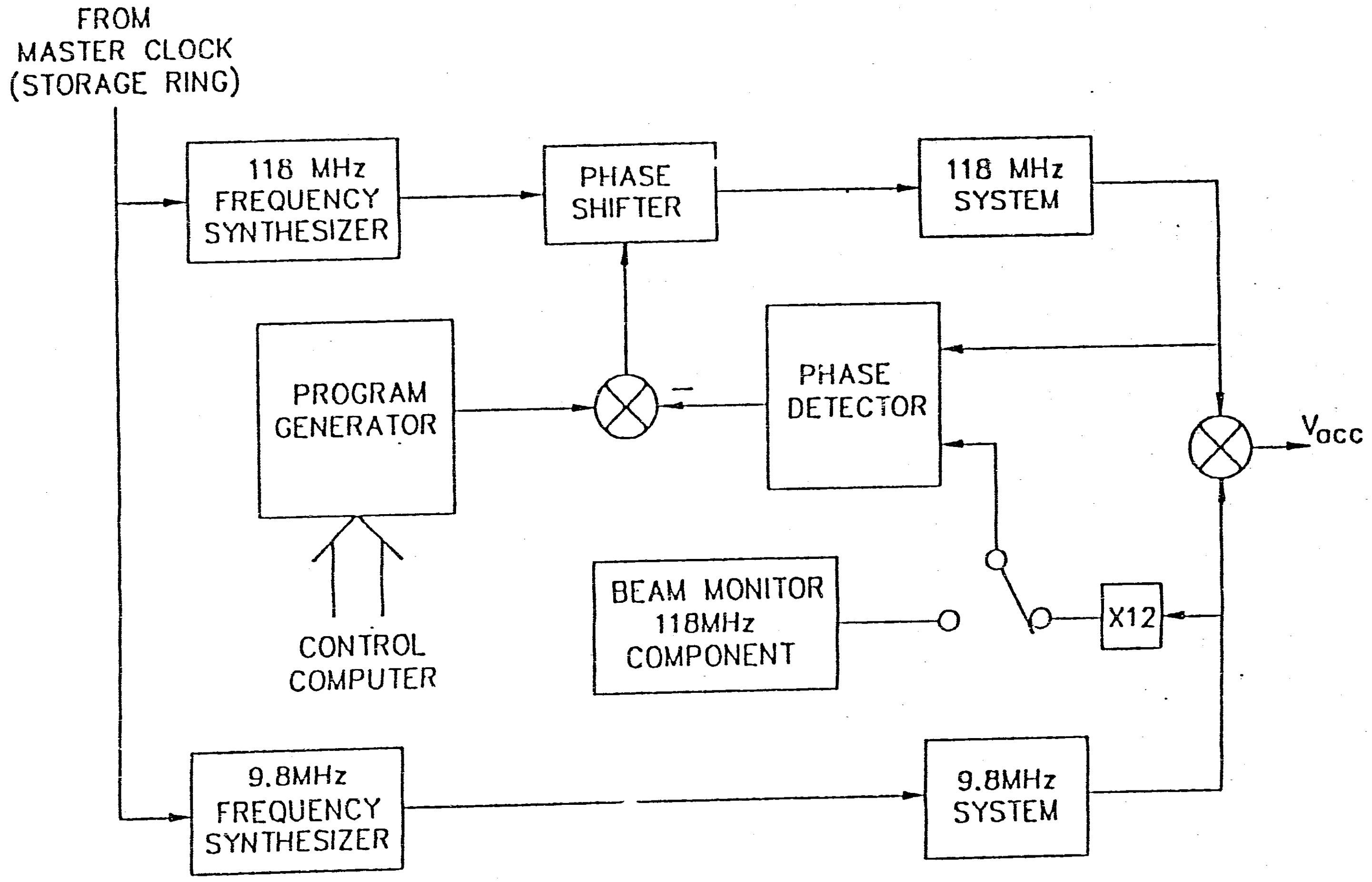


Figure 6-5 PAR RF System Showing Synchronization Scheme

Table 7-1

Injector Synchrotron RF Parameters

Parameter	Value	Unit
Circumference	368.0	m
Revolution Time	1.228	μs
Injection Energy	0.45	GeV
Nominal Energy	7.0	GeV
Maximum Energy	7.7	GeV
Repetition Time	0.5	s
Acceleration Time	0.25	s
Energy Loss Per Turn at 7 GeV	6.38	MeV/turn
Average Beam Current	4.7	mA
Energy Gain per Turn	32.0	keV
RF Parameters		
Frequency, f	351.930	MHz
Harmonic Number	432	h
Voltage, V, at 7 GeV	9.5	MV
Synchrotron Frequency, f_s, at 7 GeV	21.1	kHz

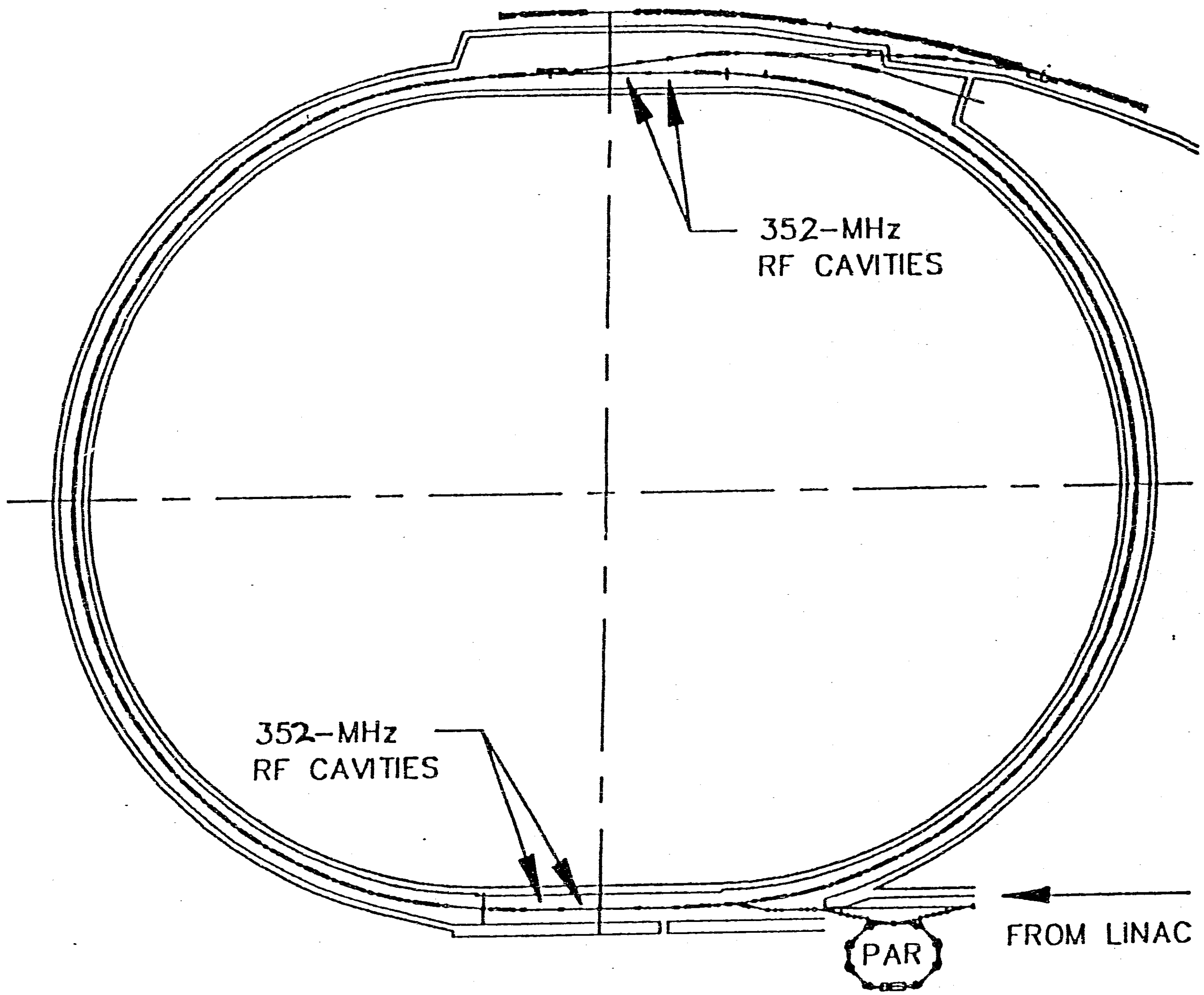
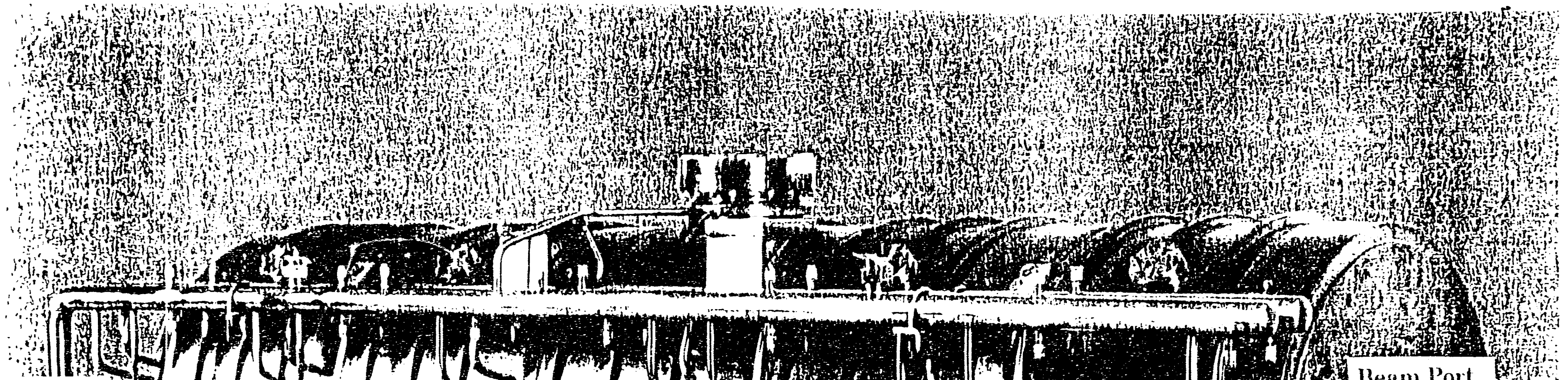
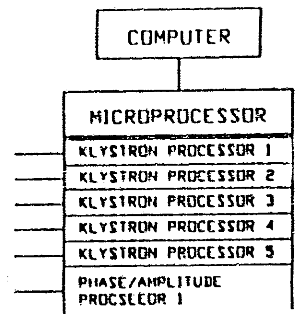


Figure 7-1 Physcial Layout of the APS Injector Synchrotron


Beam Port


COMPUTER
MICROPROCESSOR
KLYSTRON PROCESSOR 1
KLYSTRON PROCESSOR 2
KLYSTRON PROCESSOR 3
KLYSTRON PROCESSOR 4
KLYSTRON PROCESSOR 5
PHASE/AMPLITUDE PROCSECOR 1

FROM KL

Table 7-2

Parameters for the Five-Cell, λ/2, 352-MHz Cavity

Parameter	Value	Unit
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 per cavity	55.3	MΩ
Average Accelerating Voltage	1.39	MV/m
Total Power Required	546	kW
rf Power @ 2.95 MV/cavity	156.9	kW

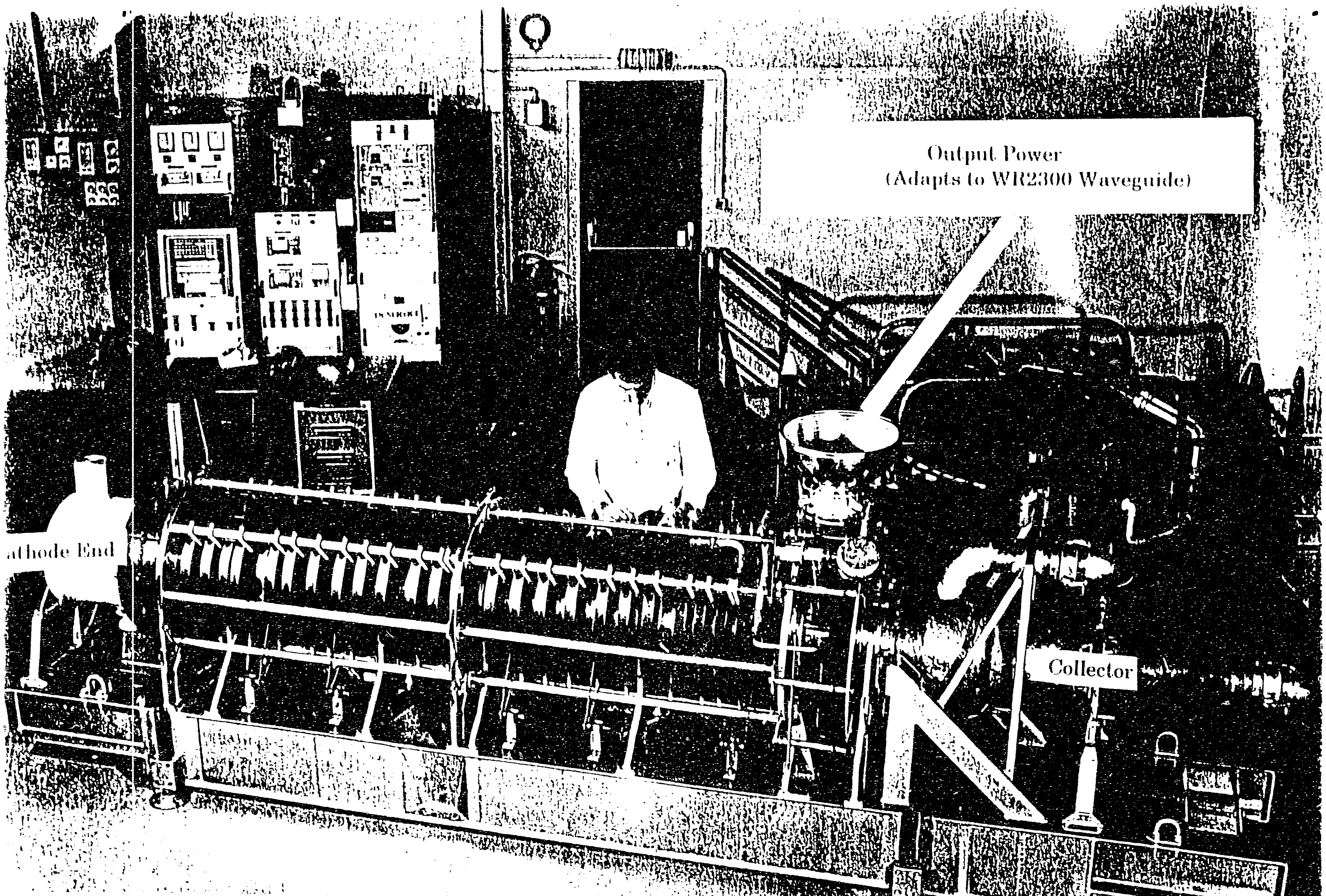


Figure 7-3 Klyston for Injector Synchrotron RF Power Amplifier System

Table 8-1

Parameters of the RF System

Harmonic number	1296			
RF frequency	351.929	MHz		
Peak voltage per turn	9.500	MV		
Number of cavities	15			
Cavity parameters:				
Max voltage (estimated)	1.00	MV		
Shunt resistance	5.60	MΩ		
Max power	89.2	kW		
Quality Factor, Q	48.6	10^3		
Operating values:	7 GeV 100 mA	7GeV 300 mA	7.5 GeV 200 mA	
Voltage per turn	9.5	9.5	12.0	MV
Voltage per cavity	633.3	633.3	800.0	kV
Power per cavity	35.8	35.8	57.1	kW
Total power	537.0	537.0	856.5	kW
Beam power per cavity	46.0	138.0	117.3	kW
Sum	81.0	173.0	174.3	kW
Q (loaded)	21.1	9.87	16.0	10^3
Bandwidth (loaded)	16.7	35.8	22.1	kHz
Power lost (source to cavity)	8.1	17.3	17.4	kW
Source power	1.34	2.85	2.87	MW

3dB bandwidth of cavity alone = 7.23 kHz

Table 8-2

Radio Frequency and Beam Parameters for 7-GeV and 100-mA Operation

Frequency	351.929	MHz
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	17.5	mm
rf-Bucket Height, $\Delta E_{rf}/E_o$ (with ID and estimated parasitic losses)	2.0% ≃ 7	σ_E/E
Synchrotron Frequency	1.96	kHz

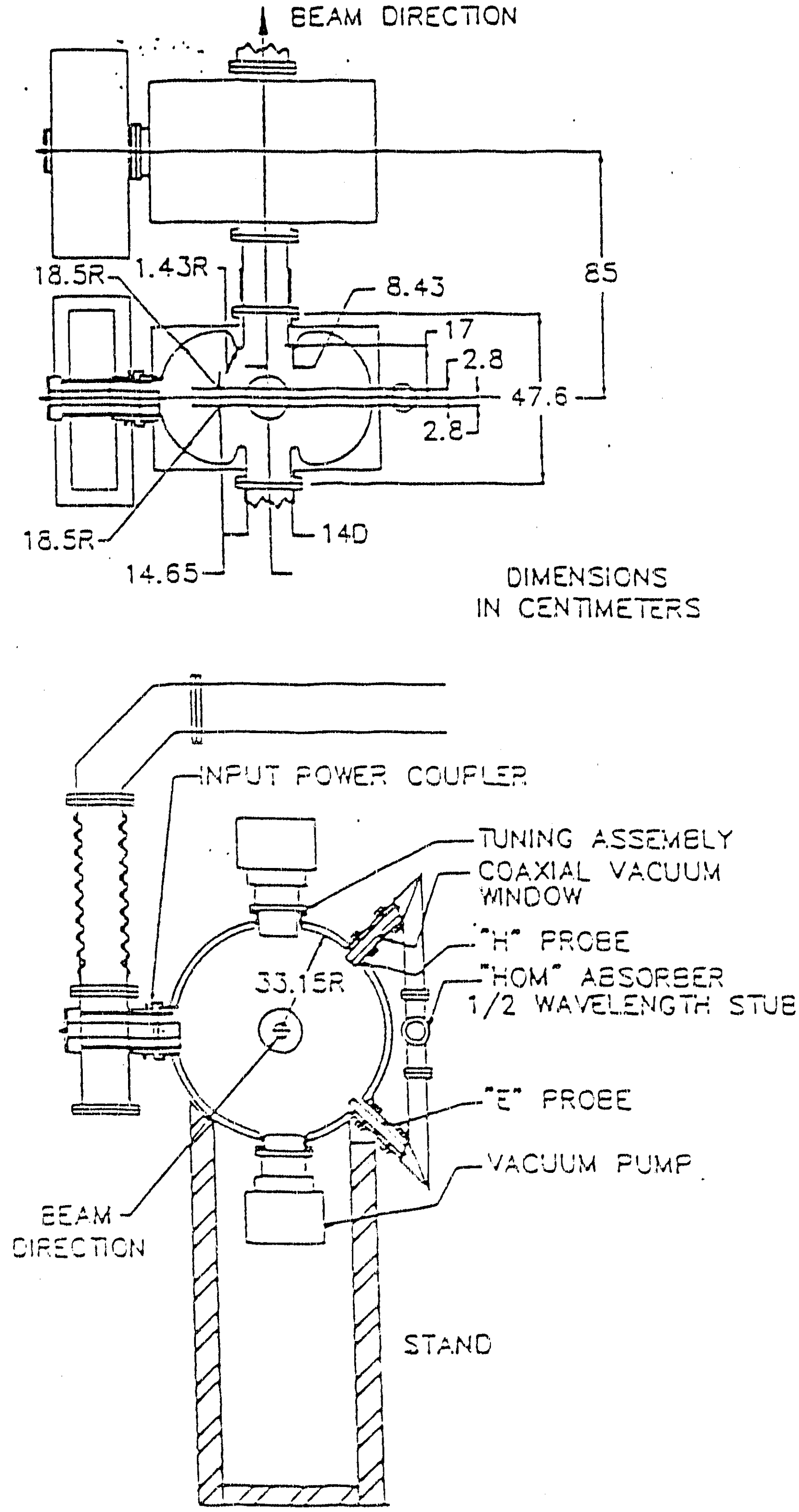


Figure 8-1 **352-MHz Accelerating Structure Showing a Top View of Two Cavities and a Vertical Cross Section**

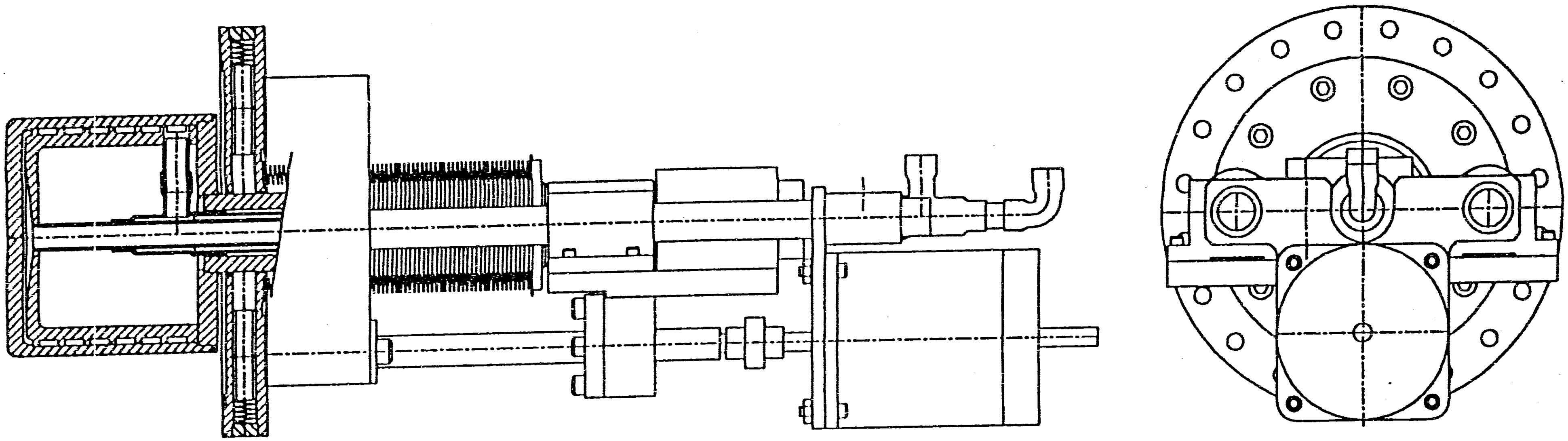


Figure 8-2 Tuner (Non-Conducting Plunger), Activated by Stepping Motor over a One MHz Range.

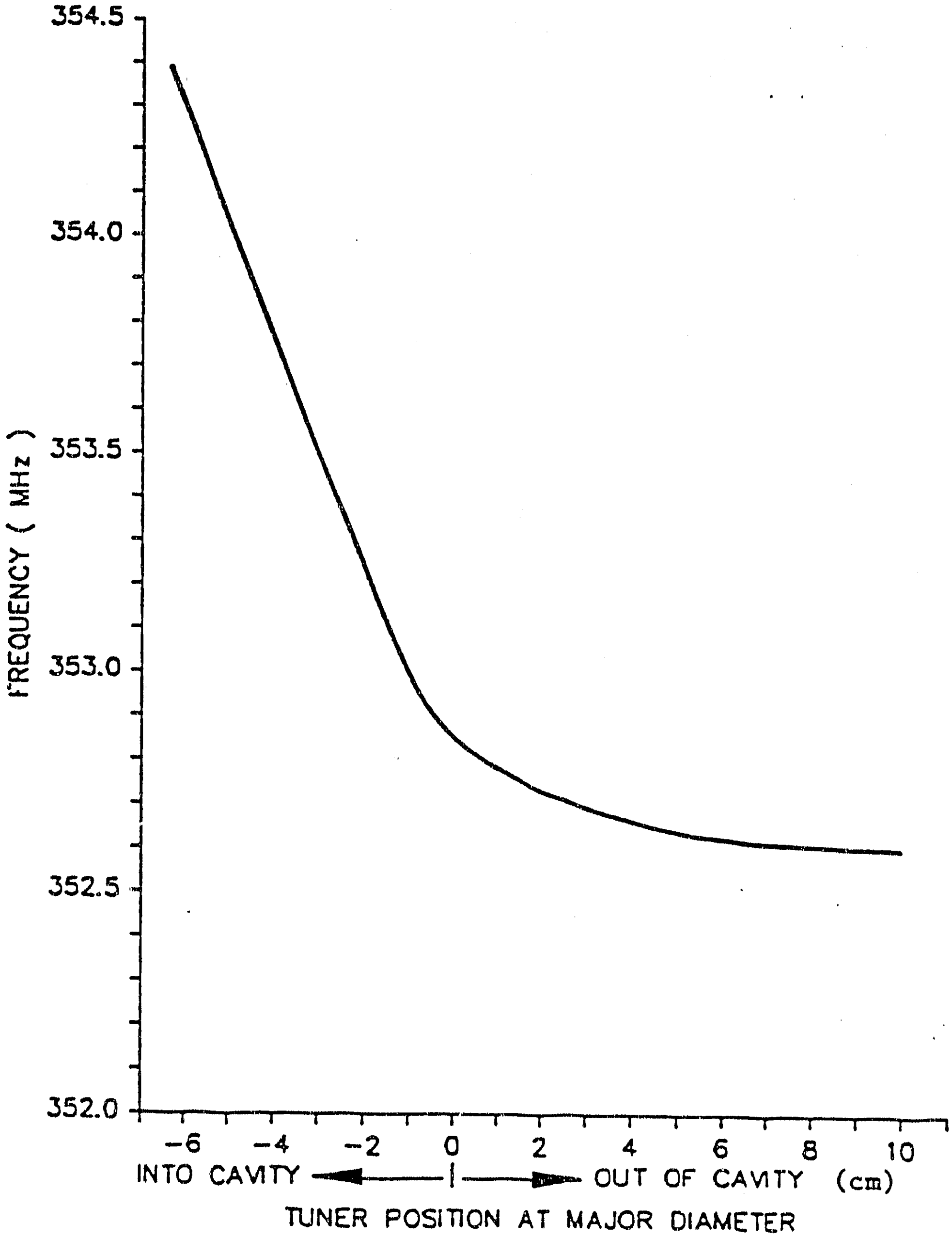


Figure 8-3 Effect of Tuner

Table 8-3

Shunt Impedances of Some of the Higher-Order Modes of the Single-Cell Spherical Cavity

Frequency MHz	Shunt Impedance (undamped) MΩ	Q (undamped)
353.0	11.23	48,600
743.0	0.03	41,630
925.0	1.25	108,800
1174	0.33	43,450
1330	0.03	129,000
1511	1.09	88,130
1654	0.07	45,770
1679	1.06	46,260
1842	0.33	121,250
1972	2.98	54,850

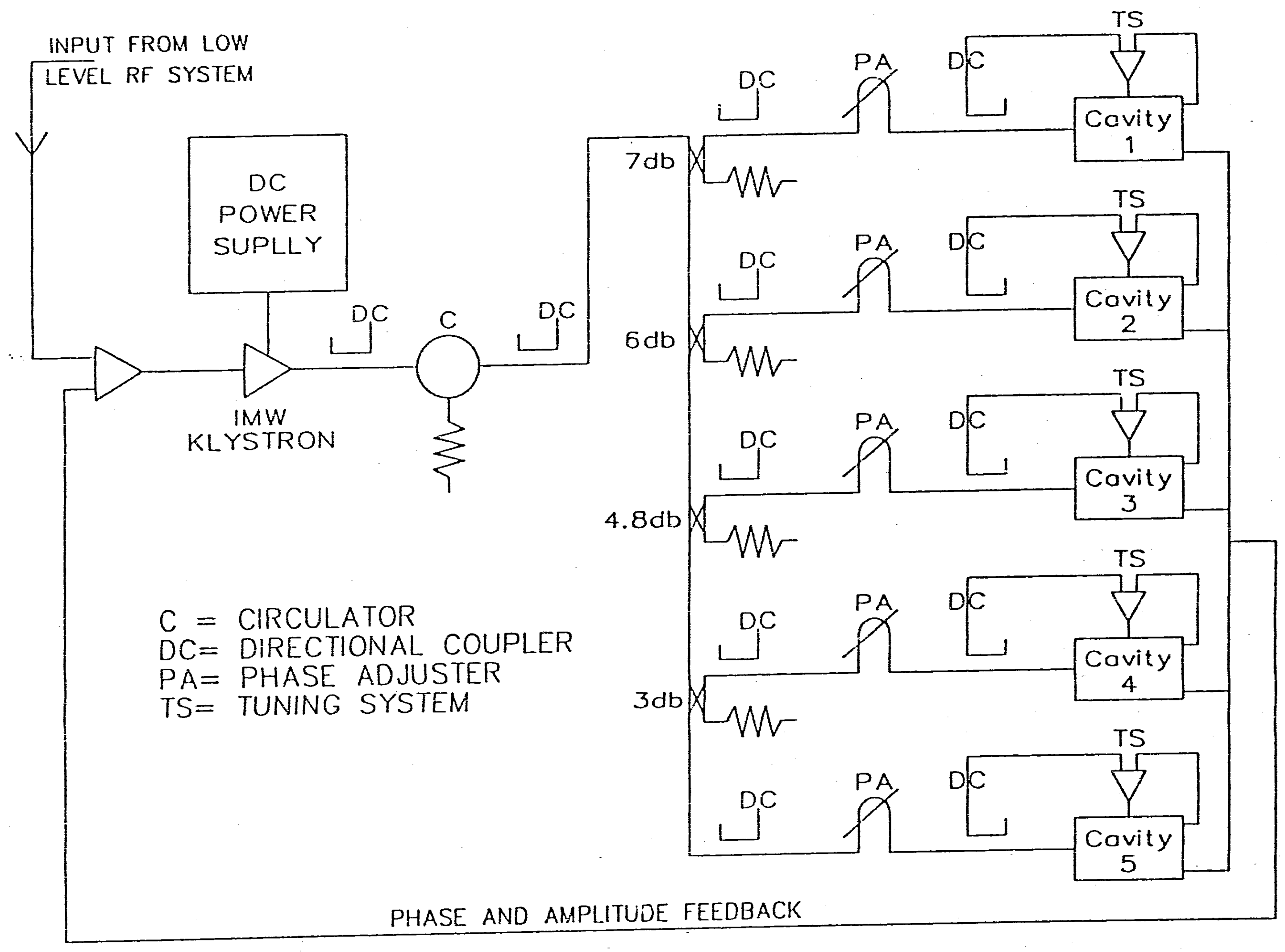


Figure 8-4 Schematic Diagram of Circuit Used to Split the Power From One 352-MHz, 1-MW Klystron and Distribute it to Five RF Cavities

Table 8-4

Parameters for the Thomson-CSF

TH 2089 1-MW, 352-MHz Klystron

Operating Frequency	352	MHz
Mechanical Tuning Range with Respect to Center Frequency	±3	MHz
Continuous Output Power	1.0	MW
Reflected Power, Maximum	16.6	kW
Drive Power, Maximum	200	W
Gain, Minimum	40	dB
Gain, Typical	41	dB
Efficiency	65-70	%
Beam Voltage	90	kV
Beam Current	18	A
Length (horizontal position)	4.8	m
Height (horizontal position)	1.85	m
Width	1.0	m
Output Waveguide	WR2300	

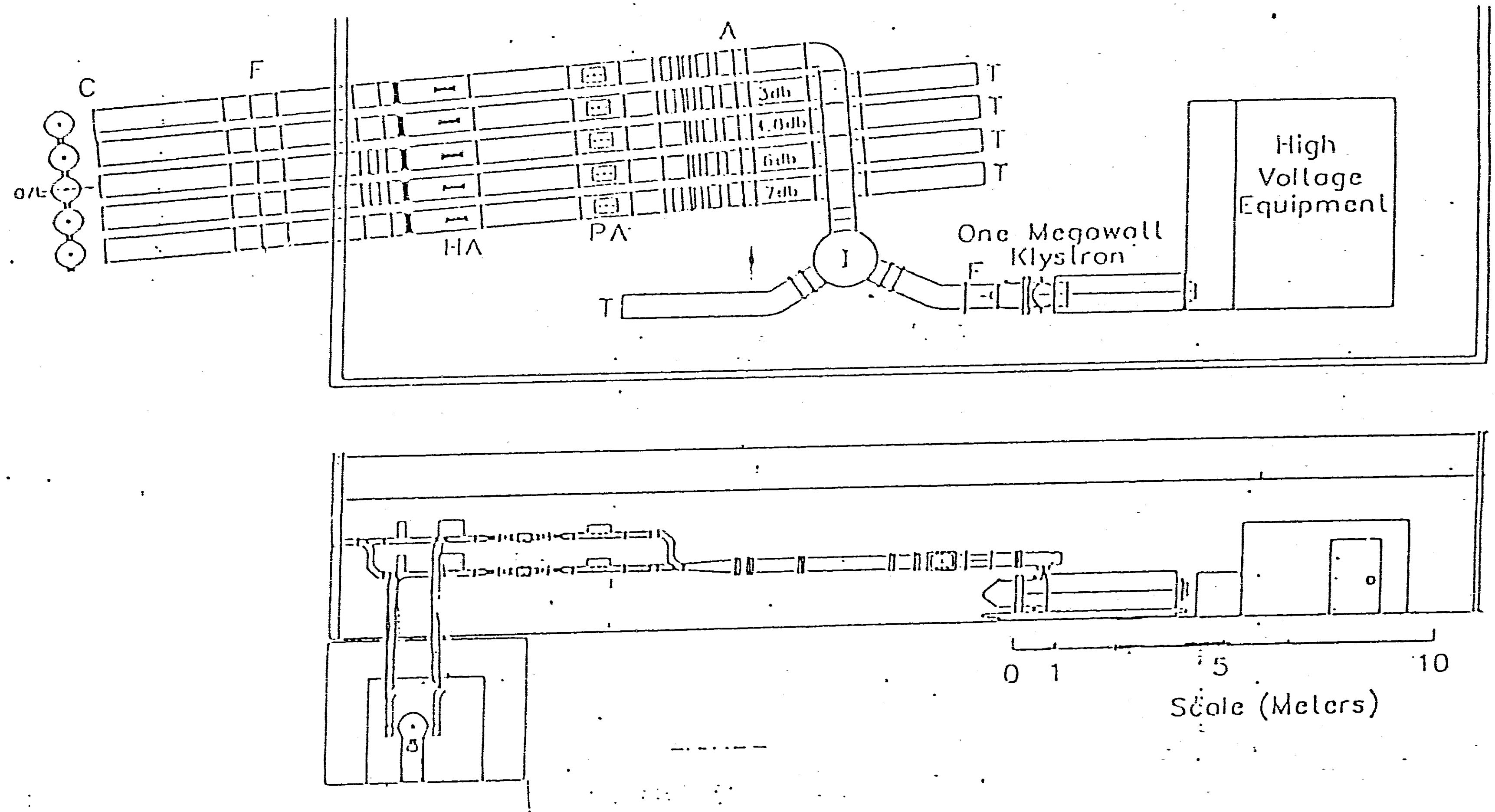


Figure 8-5 Klystron Amplifier and Cavities