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THE ADVANCED PHOTON SOURCE LIST OF PARAMETERS

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1.0 INTRODUCTION

The Advanced Photon Source (APS) is a third-generation synchrotron radiation source that stores positrons in a storage ring. The choice of positrons as accelerating particles was motivated by the usual reason: to eliminate the degradation of the beam caused by trapping of positively charged dust particles or ions. The third-generation synchrotron radiation sources are designed to have low beam emittance and many straight sections for insertion devices.

The parameter list is comprised of three basic systems: the injection system, the storage ring system, and the experimental facilities system. The components of the injection system are listed according to the causal flow of positrons. Below we briefly list the individual components of the injection system, with the names of people responsible for managing these machines in parentheses:

- the linac system; electron linac-target-positron linac (Marion White)
- low energy transport line from linac to the PAR (Michael Borland)
- positron accumulator ring or PAR (Michael Borland)
- low energy transport line from PAR to injector synchrotron (Michael Borland)
- injector synchrotron (Stephen Milton)
- high energy transport line from injector synchrotron to storage ring (Stephen Milton)

The storage ring system, managed by Glenn Decker, uses the Chasman-Green lattice. The APS storage ring, 1104 m in circumference, has 40 periodic sectors. Six are used to house hardware and 34 serve as insertion devices. Another 34 beamlines emit radiation from bending magnets. The experimental facilities system's parameters include parameters for both an undulator and a wiggler.

The parameters listed here are the result of dedicated work by APS personnel over the years. The numbers, collected from all ring managers, are the most recent ones available. If in doubt about a specific parameter, please consult the individual managers of the appropriate machines as listed above. If there are any further *approved* changes, I would appreciate being told, so the parameters may be updated. It is in everyone's best interest to keep the parameter list current.

Hana M. Bizek, ASD

2.0 INJECTION SYSTEM

The Injection System supplies a 7-GeV positron beam for injection into the storage ring and is composed of the following component systems.

2.1 Linear Accelerator (Linac)

The Advanced Photon Source linac system consists of a 200-MeV, 2856-MHz, S-band electron linac and a 2-radiation-length-thick tungsten target followed by a 450-MeV positron linac. It achieves the design goal for positron current of 8 mA and produces electron energies up to 650 MeV without the target in place.

The linac is designed to accelerate 30 ns-long pulses containing 50 nC of electrons to an energy of 200 MeV at 48 pulses per second. The 480-W beam is focused to a 3-mm-diameter spot on a 7-mm-thick tungsten target that serves as a positron converter. Bremsstrahlung-pair-produced (BPP) positrons and electrons are refocused by a 1.5-T pulsed coil and are directed into the positron linac. Both electrons and positrons are captured and can be accelerated to about 450 MeV.

Parameters of the linacs are given below.

2.1.1 General

Electron Linac	200	MeV
Positron Linac	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	

2.1.2 Electron Linac

Gun voltage	110	kV
Prebuncher, type SW, single-gap re-entrant cavity		
Buncher TW, β=.75 constant impedance, 5 cavities		
Number of TW accelerating sections	5	
Pulse repetition rate	48	pps; 24 contiguous 16.7 ms apart every 1/2 second
Beam pulse length	30	ns
Pulse current	1.7	A
Emittance, 95th percentile	< 1.2	mm-mrad
Bunch length (90% of particles)	< 0.2618	rad
Energy spread	± 8	%

2.1.3 Target

Target material	Tungsten	
Target thickness, (2Xo)	7	mm
e^- beam diameter on target	≤ 3	mm
Average incident power	480	W
Pulsed solenoidal field	1.5	T
Conversion efficiency e^+ / e^- at target	0.0083	
Mean energy of positrons from target	8	MeV

2.1.4 Positron Linac

Linac output energy	450	MeV
Linac output current	8	mA
Emittance, 95th percentile	6.6	mm-mrad
Energy spread, 95th percentile	≤ 0.01	
Number of TW sections	9	
Final e^+ / e^- efficiency	0.005	

2.1.5 Beam Diagnostics (number of each type)

Current monitors, consisting of	
Faraday cups (FC)	3
Wall current monitors (WCM)	3
Average current monitors (ACM)	4
Toroidal coil	1
Beam position monitors (BPMs)	12
Loss monitors	14
Fluorescent screens	10

2.2 LTP (Linac to PAR) Transport Line

The first section of the 450-MeV positron beam transport line from the positron linac to the PAR contains 10 quadrupoles and one bending dipole.

Parameters of the low energy transport line between linac and PAR are given below.

2.2.1 Magnets

Dipoles		
Number	1	
Magnetic length	0.4	m
Bending angle	0.2	rad
Field	0.75	T
Quadrupoles		
Number	10	
No. of independent power supplies	10	
Magnetic length	0.3	m
Max gradient	12.7	T/m
Pole tip inscribed radius	32	mm

2.2.2 Beam Diagnostics (number of each type)

Current monitor	1	
Position monitors	4	per plane
Loss monitor	1	
Fluorescent screens	3	

LTP parameters for beam diagnostics

Peak current (linac output)	8	mA
Bunch length (from linac)	30	ns
Intensity per pulse	1.5×10^9	e^+
Charge per pulse	240	pC
Number of pulses	24	
Pulse repetition rate	60	Hz

2.3 Positron Accumulator Ring (PAR)

The PAR is a DC storage ring with a circumference of 30.667 m (1/12 of the injector synchrotron). The 450-MeV positrons from the positron linac are injected and accumulated in the horizontal phase space of the PAR at a 60-Hz rate. As many as 24 linac macropulses can be accumulated as a single bunch in the PAR during each 0.5-s cycle of the injector synchrotron. This leaves 0.1 s for final compression of the PAR bunch length before extraction and injection into one of the 352-MHz rf buckets of the injector synchrotron.

The 30-ns positron pulses are accumulated in a first harmonic 9.8-MHz rf system operating at 40 kV. A 30-kV, 12th harmonic cavity is turned on for the final compression of the accumulated bunch length. The total number of positrons injected into the PAR can be as large as 3.6×10^{10} (24 pulses $\times 1.6 \times 10^{9}$/pulse).

Parameters of the PAR are given below.

2.3.1 PAR Technical Components

2.3.1.1 Magnets

Main dipoles (DC)		
Number	8	
Effective length	0.8	m
Bending radius	1.0196	m
Field strength	1.472	T
Aperture vacuum chamber	3.8×11.0	cm
Quadrupoles (DC)		
Number	16	
Effective length	0.23	m
Field gradient	4	T/m
12-Pole Correction (DC)		
Number	10	
Effective length	0.2	m
Dipole field strength	0.015	T
Sextupole field gradient	12	T/m^2
Kickers		
Number	3	
Effective length	0.35	m
Field strength	0.043	T
Rise time	190	ns
Flat top	30	ns
Fall time	100	ns
Rep. rate	60	Hz
Gap	5.3	cm
AC Septum		
Number	1	
Effective length	0.4	m
Field strength	0.75	T
Septum thickness	2	mm
Aperture	7.0×2.0	cm

2.3.1.2 Vacuum System

Vacuum chamber cross section	Rectangular shape	
	3.9×12.2	cm
Chamber wall thickness	2	mm
Formed shape	To fit magnet curvature	
Material	Inconel	
Circumference	30.7	m
Outgassing rate	1.0×10^{-11}	$\mathrm{Torr} \cdot \ell / (\mathrm{s} \cdot \mathrm{cm}^2)$
Design average pressure	10	nTorr or better

2.3.1.3 RF Systems

System I		
Frequency, f	9.77583	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	117.3099	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

2.3.1.4 Beam Diagnostics (number of each type)

DC current monitor, 100 mA	1	
Beam position monitors, ± 0.2 mm on closed orbit	16	
Tune measuement system	1	
Segmented beam loss monitors	4	
Fluorescent screen monitors for injection	6	
Movable beam aperture scraper	1	per plane
Photon beam monitor stations for emittance and bunch length	2	

2.3.2 Lattice and Orbit Parameters

Circumference	30.6667	m
Revolution time	102.293	ns
Energy	450	MeV
Number of cells	2	
Number of bending magnets	8	
Dipole field B	1.472	T
Bend radius, ρ	1.0196	m
Number of quadrupoles	16	
Tunes		
Horizontal	2.170	
Vertical	1.217	
Transition gamma	2.01	
Uncorrected chromaticities		
Horizontal	-0.25	
Vertical	-4.07	
Partition numbers, $J_x / J_y / J_e$	1.242 / 1.000 / 1.758	
Damping time constants, $t_x / t_y / t_e$	20.8 / 25.8 / 14.7	ms
Energy loss per turn	3.56	keV
Natural emittance	0.36	mm-mrad
Natural energy spread (damped)	0.41×10^{-3}	
Minimum average beam current	2.35	mA
Design average beam current	56.31	mA
Number of bunches	1	
Maximum intensity (with 24 linac pulses injected)	3.6×10^{10}	

2.3.3 Lattice Components for 1/4 Machine ($B\rho$ = 1.5010 T·m at 0.45 GeV)

Element	Length (m)	Magnetic strength ρ, $B'/B\rho$, $B''\ell/B\rho$ (m, m^{-2}, m^{-2})
L	1.731675	
S1	0.20	
L	0.08	
Q1	0.23	1.7860 m^{-2}
L	0.24	
M	0.80	1.01961 m
L	0.24	
Q2	0.23	2.2959 m^{-2}
L	1.47	
SD	0.20	1.1917 m^{-2}
L	0.08	
Q3	0.23	0.0000 m^{-2}
L	0.24	
M	0.80	1.01961 m
L	0.24	
Q4	0.23	2.2702 m^{-2}
L	0.325	
1/2 SF	0.10	-0.1655 m^{-2}
(Reflection Point)		
Total	7.666675	

L=drift, M=bending magnet, Q=quadrupole, S=sextupole

2.3.4 PAR Tolerances

Quadrupole placement	0.5×10^{-3}	m
Sextupole placement	0.5×10^{-3}	m
Dipole roll	0.5×10^{-3}	

2.4 PTB (PAR to Booster) Transport Line

The second section of the 450-MeV positron beam transport line from the PAR to the injector synchrotron (also known as booster) contains 11 quadrupoles and two horizontal bends. The two bends in opposite polarities form an achromatic horizontal parallel translation together with four quadrupoles.

Parameters of the low energy transport line from PAR to injector synchrotron (or booster) are given below.

2.4.1 Magnets

Dipoles		
Number	2	
No. of independent power supplies	2	
Magnetic length	0.4	m
Bending angle	0.2	rad
Field	0.75	T
Bending angle	0.187	rad
Field	0.703	T
Quadrupoles		
Number	11	
No. of independent power supplies	11	
Magnetic length	0.3	m
Max gradient	12.7	T/m
Pole tip inscribed radius	32	mm

2.4.2 Beam Diagnostics (number of each type)

Current monitor	1	
Position monitors	5	per plane
Loss monitor	1	
Fluorescent screens	3	

PTB parameters for beam diagnostics

Peak current (assume Gaussian bunch)	7.92	A
Bunch length (from the PAR)	0.29	ns
Intensity per bunch, at 100% efficiency	3.6×10^{10}	e^+
Charge per pulse, at 100% efficiency	5.76	nC
Pulse repetition rate	2	Hz

2.5 Injector Synchrotron (Booster)

The injector synchrotron has a circumference of 368 m (one-third that of the storage ring) and operates at a repetition rate of 2 Hz. Once each cycle the positron bunch accumulated in the PAR is transferred to the injector synchrotron for acceleration to 7 GeV. At 7 GeV the beam bunch is extracted and transported to the storage ring for injection.

The parameters of the injector synchrotron are given below.

2.5.1 Injector Synchrotron Technical Components

2.5.1.1 Magnets and Power Supplies

Dipoles		
Number	68	
No. of master/slave power supplies	2	
Magnetic length	3.077	m
Bending radius	33.3009	m
Dipole field at 7 GeV	0.7011	T
Total width of poles	11.43	cm
Total gap height	4	cm
Quadrupoles		
Number	80	
No. of independent power supplies, QF, QD	2	
No. in family QF	40	
No. in family QD	40	
Magnetic length	0.5	m
Max. gradient at 7 GeV	16.6	T/m
Total bore radius	2.828	cm
Sextupoles		
Number	64	
No. of independent power supplies, SF, SD	2	
No. in family SF	32	
No. in family SD	32	
Magnetic length	0.1	m
Max. strength	248	T/m^2
Total bore radius	3.5	cm
Correction dipoles		
Horizontal correctors		
Number	40	
No. of independent power supplies	40	
Magnetic length	0.1155	m
Peak field	0.12	T
Gap height	4	cm
Vertical correctors		
Number	40	
No. of independent power supplies	40	
Magnetic length	0.1435	m
Peak field	0.15	T

2.5.1.2 Injection Equipment

AC septum, pulsed

Number	1	
Minimum septum thickness	2.0	mm
Physical length	0.9	m
Effective length	0.8	m
Bending angle	0.2718	rad
Peak field at 450 MeV	0.51	T
Gap height	30	mm

Kicker

Number	1	
Magnetic length	0.25	m
Deflection angle	3.84	mrad
Field at 450 MeV	0.0231	T
Gap	40	mm
Rise time	500	ns
Flat top	30	ns
Fall time	500	ns

2.5.1.3 Extraction Equipment

Septum, thin

Number	1	
Minimum septum thickness	2.0	mm
Physical length	1.06	m
Effective length	1.05	m
Bending angle	32.76	mrad
Peak field at 7 GeV	0.73	T
Maximum field	0.8	T
Gap height	20	mm
Gap width	34	mm

Septum, thick, AC

Number	1	
Minimum septum thickness	30	mm
Physical length	1.79	m
Effective length	1.75	m
Bending angle	73.53	mrad
Peak field at 7 GeV	0.98	T
Maximum field	1.1	T
Gap height	30	mm
Gap width	40	mm

Kicker

Number	1	
Length	0.8	m
Bending angle	2.13	mrad
Field at 7 GeV	0.062	T
Maximum field	0.069	T
Field gap	40	mm

2.5.1.4 Vacuum System

Vacuum chamber	Elliptical shape	
Major axis	6 cm	
Minor axis	3.7 cm	
Formed shape	To fit magnet curvature	
Material	316L stainless steel	
Circumference	368	m
Outgassing rate	9×10^{-10}	Torr·ℓ/(s·cm^2)
Chamber wall thickness	1	mm
Average chamber pressure	4×10^{-7}	Torr

2.5.1.5 RF System

Frequency	351.930	MHz
Number of cavities	4	
Number of cells per cavity	5	
Harmonic number	432	
Peak effective voltage at 7 GeV	9.5	MV
Available voltage	12.0	MV
Shunt impedance per cavity	55.3	MΩ
Active length per cavity	2.12	m
Effective shunt impedance	221	MΩ
Peak fundamental mode cavity dissipation (4 cavities at 7 GeV)	475	kW
Synchrotron radiation loss per turn at 7 GeV	6.38	MeV/turn
Synchrotron radiation power at 4.7 mA and at 7 GeV	30.0	kW
Waveguide and other losses, 10%	50.5	kW
Total peak power required at 7 GeV	555	kW
RF power available	1000	kW

2.5.1.6 Beam Diagnostics (number of each type)

Current monitor (10 mA peak)	1
Beam position monitors ± 0.1 mm on closed orbit	80
Tune measurement system	1
Segments of beam loss monitors	4
Fluorescent screen monitors for injection	5
Set of beam scrapers, 1 vertical jaws and 1 horizontal	1
Photon beam monitor stations for emittance and bunch length	3

2.5.2 Lattice and Orbit Parameters

Circumference	368.0	m
Revolution time	1.228×10^{-6}	s
Ramping repetition rate	2	Hz
Acceleration time	0.23	s
Harmonic number	432	
Radio frequency	351.93	MHz
Lattice structure	10 FODO cells per quadrant	
Number of superperiods	2	
Normal FODO cells per quadrant	8	
Dispersion suppressor FODO cells per quadrant	1	
Dispersion arc FODO cells per quadrant	1	
Total number of cells	40	
Total number of bending magnets	68	
Magnetic field at: Injection	0.0451	T
Extraction	0.7012	T
Mean radius	58.57	m
Bending radius	33.3009	m

2.5.3 Performance Parameters

Nominal energy	7.0	GeV
Max energy	7.7	GeV
Injection energy	> 350	MeV
Cycle rate	2	Hz
Average beam current	4.7	mA
Peak beam current	30	A
Number of positrons/cycle	3.6×10^{10}	
Injected beam emittance at 450 MeV	0.37×10^{-6}	m-rad
Longitudinal bunch area at 450 MeV	2.7×10^{-2}	eV-s
Natural emittance at 7 GeV	1.34×10^{-7}	π m-rad
Energy spread, rms, at 7 GeV	1.0×10^{-3}	
Energy gain per turn	35.0	keV
Bunch length σ_τ, natural at 7 GeV	76	ps
Number of bunches	1	

2.5.4 Tolerances, rms

Dipole placement error		
Radial	1	mm
Vertical	0.5	mm
Longitudinal	1	mm
Random dipole roll angle error	1	mrad
Quadrupole placement error		
Radial	0.3	mm
Vertical	0.3	mm
Longitudinal	1	mm
Random quadrupole roll angle error	0.5	mrad
Sextupole placement error		
Radial	0.36	mm
Vertical	0.36	mm
Longitudinal	1	mm
Random sextupole roll angle error	1	mrad
Correcting dipole placement error	3 - 5	mm
Correcting dipole roll angle error	1	mrad

2.5.5 Injector Synchrotron Cell (Length=9.20 m, $B\rho$ =23.3495 T· m)

Element	Length (m)	Magnetic strength B, B', B'' (7 GeV) (T, T / m, T / m^2)
QD	0.5	-14.9033
L	0.1465	
SD	0.1	-247.996
L	0.265	
M	3.077	0.7011659
L	0.31325	
HC	0.1155	±0.15
L	0.08275	
QF	0.5	16.5913
L	0.1465	
SF	0.1	137.0129
L	0.265	
M	3.077	0.7011659
L	0.29925	
VC	0.1435	± 0.12
L	0.06875	

L=drift, M=bending magnet, Q=quadrupole, S=sextupole, C=corrector

Betatron tunes		
Horizontal	11.759	
Vertical	9.800	
Synchrotron frequency at 7 GeV	21.1	kHz
Natural chromaticities		
Horizontal	-15.4	
Vertical	-13.1	
Beta functions		
Maximum horizontal	16.97	m
Minimum horizontal	2.1	m
Maximum vertical	16.65	m
Minimum vertical	2.7	m
Maximum dispersion	1.24	m
Momentum compaction	9.66×10^{-3}	
Transition gamma	10.17	
Damping time at 7 GeV		
Horizontal	2.74	ms
Vertical	2.69	ms
Longitudinal	1.34	ms
Number of sextupole families	2	
Energy loss per turn at 7 GeV	6.38	MeV
Beam elevation above floor	1.4	m

2.6 BTS (Booster to Storage Ring) Transport Line

The 7-GeV positron beam bunch accelerated in the injector synchrotron is transported to the storage ring for injection into a predesigned rf bucket every one-half second. The transport line consists of 12 quadrupoles and four horizontal bends. Two equal and opposite sets of septum magnets are used for extraction from the synchrotron and injection into the storage ring. The bends make up for the difference in orientation between the synchrotron orbit at extraction and the storage ring orbit at injection. The quadrupoles are arranged and powered to match the machine parameters of the booster to those of a stored beam in the storage ring.

Parameters of the high energy transport line are given below.

2.6.1 Magnets

	Main Transport Line to Ring	Branch Line to Beam Dump	
Dipoles			
Number	4	1	
Magnetic length	1.95	1.95	m
Bending angle	0.07744	0.07744	rad
Field at 7 GeV	0.93	0.93	T
Gap	34	34	mm
Quadrupoles			
Number	12		
Magnetic length	0.6		m
Max gradient at 7 GeV	17		T/m
Pole tip inscribed radius	17		mm

2.6.2 Beam Diagnostics (number of each type)

Current monitor for transmission efficiency	1
Beam position monitors for beam steering (six for horizontal and seven for vertical positions)	13
Fluorescent screen monitors for initial steering	5
Loss monitor	1
Vertical scraper sets (upper/lower)	2

BTS Parameters for Beam Diagnostics

Peak current (assume Gaussian bunch)	30	A
Bunch length (from injector synchrotron)	76	ps
Intensity per pulse	3.6×10^{10}	e^+
Charge per pulse	5.76	nC
Pulse rate	2	Hz

3.0 STORAGE RING SYSTEM

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 radiation of high brilliance over a wide range of wavelengths. The general design performance parameters of the storage ring are given below.

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}	
Design circulating current, single bunch	5	mA
Number of stored positrons, single bunch	1.2×10^{11}	
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 design bunch current	2.9×10^{-3}	
Bunch length, rms, natural	5.3	mm
Bunch length, FWHM, natural	34.6	ps
Bunch length, FWHM, design bunch current	104.0	ps
Max energy	7.7	GeV
Beam lifetime, mean-life		
Gas scat, 8-mm vert gap, 1 nTorr 75% H_2 & 25% CO	76	h
Touschek, design bunch current, 10% coupling	190	h
Filling rate (from booster)	3.6×10^{10}	e^+/s
Filling time		
Multibunch, to 100 mA	1.1	min

3.1 Storage Ring Technical Components

The storage ring consists of the following technical components.

3.1.1 Magnets and Power Supplies System

There are five types of magnets:

Dipole
Quadrupole — 0.8 m, 0.6 m, and 0.5 m
Sextupole
Skew Quadrupole
Correction Dipole — combined horizontal / vertical

The parameters of the system are given below.

Dipoles		
Number	80 + 1	
No. of independent power supplies	1	
Magnetic length	3.06	m
Core length	3.00	m
Bending radius	38.9611	m
Field	0.599	T
Dipole trim coils		
Number	80 + 1	
No. of independent power supplies	80	
Magnetic length	3.06	m
Field	0.04	T
Quadrupoles, 0.8 m		
Number	80	
No. of independent power supplies	80	
Magnetic length	0.8	m
Core length	0.765	m
Max. gradient	18.9	T / m
Quadrupoles, 0.6 m		
Number	80	
No. of independent power supplies	80	
Magnetic length	0.6	m
Core length	0.565	m
Max. gradient	18.9	T / m
Quadrupoles, 0.5 m		
Number	240	
No. of independent power supplies	240	
Magnetic length	0.5	m
Core length	0.465	m
Max. gradient	18.9	T / m
Skew quadrupoles		
Number	20	
Magnetic length	0.128	m
Core length	0.082	m
Max. gradient	3.0	T / m
Sextupoles		
Number	280	
Magnetic length	0.253	m
Core length	0.223	m
Max. strength	405	T / m^2

3.1.1.1 Design Specification Parameters for the Storage Ring Horizontal / Vertical Correction Dipole Magnets

	H-Corrector		V-Corrector	
Number	317		317	
Magnetic length	0.160	m	0.167	m
Core length	0.07	m	0.07	m
Peak field at 7.0 GeV	0.16	T	0.17	T
Peak bend angle	1.1	mrad	1.2	mrad

3.2 Lattice and Orbit Parameters

The magnets are arranged in a regular lattice around the 1104-m-circumference ring in 40 cells forming 40 zero-dispersion, 5.2-m-long straight sections to accommodate insertion devices. The straight sections are joined by two-bend achromatic sections. This so-called Chasman-Green lattice produces a low emittance and hence a narrow beam.

The ring lattice and the resultant orbit parameters are given below.

Circumference	1104	m
Revolution time	3.683×10^{-6}	s
Revolution frequency	271.5	kHz
Radio frequency	351.927	MHz
RF voltage	9.5	MV
Harmonic number	1296	
Minimum rms momentum spread	9.6×10^{-4}	
Parameters corresponding to loss from dipoles only:		
Energy loss	5.45	MeV/turn
Bucket half-height	2.8	%
Synchrotron frequency	1.96	kHz
Minimum rms bunch length	0.53	cm
Radiation loss, insertion devices, max.	1.25	MeV/turn
Parameters corresponding to loss from dipoles, IDs and HOMs:		
Energy loss	6.9	MeV/turn
Bucket half-height	2.0	%
Synchrotron frequency	1.80	kHz
Minimum rms bunch length	0.58	cm
Number of periods	40	
Length available for insertion device	5.2	m
Mean radius	175.7	m
Bending field	0.599	T
Bending radius	38.9611	m
Maximum quadrupole strength	18.9	T/m
Injection energy	Full energy	
Number of dipoles per period	2	
Number of quadrupoles per period	10	
Number of chromatic sextupoles per period	3	
Number of harmonic sextupoles per period	4	

3.2.1 Cell Parameters (7 GeV, $B\rho = 23.3495\ \text{T} \cdot \text{m}$)

Element	Effective length (m)		Magnetic strength
	Nominal	Avg. measured	B', ρ, $B''\ell / B\rho$
L	3.036		
VHC			
L	0.324		
Q1	0.50	0.4935	-10.7791 T / m
L	0.1142		
BPM			
L	0.3758		
VHC			
L	0.17		
Q2	0.80	0.7924	15.0266 T / m
L	0.0847		
BPM			
L	0.0889		
S1	0.2527		1.6572 m^{-2}
L	0.1737		
Q3	0.50	0.4938	-9.5795 T / m
L	0.52		
VHC			
L	0.3136		
S2	0.2527		-3.3317 m^{-2}
L	0.1047		
BPM			
L	0.1190		
M	3.06		38.9611 m
L	0.1537		
BPM			
L	0.0700		
S3	0.2527		-4.1783 m^{-2}
L	0.7836		
Q4	0.50	0.4900	-19.2990 T / m
L	0.1750		
VHC			
L	0.1750		
Q5	0.60	0.5915	18.6255 T / m
L	0.1736		
S4	0.1264		1.9126 m^{-2}
S4	0.1264		1.9126 m^{-2}
L	0.1007		

Element	Effective length (m)		Magnetic strength
	Nominal	Avg. measured	B', ρ, B''ℓ / Bρ
BPM			
L	0.0729		
Q5	0.60	0.5915	18.6255 T / m
L	0.1750		
VHC			
L	0.1750		
Q4	0.50	0.4900	-19.2990 T / m
L	0.7836		
S3	0.2527		-4.1783 m^{-2}
L	0.1047		
BPM			
L	0.1190		
M	3.06		38.9611 m
L	0.1536		
BPM			
L	0.0700		
S2	0.2527		-3.3317 m^{-2}
L	0.1377		
VHC			
L	0.6960		
Q3	0.50	0.4938	-9.5795 T / m
L	0.1737		
S1	0.2527		1.6572 m^{-2}
L	0.0943		
BPM			
L	0.0793		
Q2	0.80	0.7924	15.0266 T / m
L	0.17		
VHC			
L	0.4008		
BPM			
L	0.0892		
Q1	0.50	0.4935	-10.7791 T / m
L	0.324		
VHC			
L	3.036		

L=drift, M=bending magnet, Q=quadrupole[1], S=sextupole
BPM=beam position monitor, VHC=vertical-horizontal corrector

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[1] A positive sign indicates a horizontally focusing quadrupole.

Betatron tunes		
Horizontal	35.22	
Vertical	14.30	
Synchrotron tune	0.0072	
Natural chromaticities		
Horizontal	-64.7	
Vertical	-26.4	
Maximum beta functions		
Horizontal	24.1	m
Vertical	21.4	m
Natural emittance	8.2	nm-rad
Emittance, with 10% coupling ratio		
Horizontal	7.5	nm-rad
Vertical	0.75	nm-rad
Beta functions at insertion symmetry points		
Horizontal	14.2	m
Vertical	10.0	m
Maximum dispersion	0.40	m
Ring acceptance		
Horizontal	18.3	mm-mrad
Vertical, commissioning phase	20.41	mm-mrad
Vertical acceptance with undulators, Phase I	3.36	mm-mrad
Vertical acceptance with undulators, Phase II	1.50	mm-mrad
Beam size at insertion symmetry point, rms		
Horizontal, 10% coupling ratio	325	µm
Vertical, 10% coupling ratio	86	µm
Beam divergence at insertion symmetry point, rms		
Horizontal, 10% coupling ratio	23	µrad
Vertical, 10% coupling ratio	9	µrad
Momentum compaction factor	2.28×10^{-4}	
Transition gamma	66.24	
Damping time		
Horizontal	9.46	ms
Vertical	9.46	ms
Longitudinal	4.73	ms
Bending magnet critical energy	19.5	keV
Beam elevation above floor	1.4	m

3.3 Storage Ring Tolerance Tables

3.3.1 Orbit Positioning and Stability

The positron beam must not jitter or drift by more than 10% of its phase space area. This translates into 5% along any phase-space direction, either position or angle. Using the beta functions at the center of the APS insertion devices, this translates into

$\Delta x < 16$ microns　　$\Delta x' < 1.20$ microradians
$\Delta y < 4.4$ microns　　$\Delta y' < 0.45$ microradians

RF Position Monitors

Stability:	Long Term	30	microns
Resolution:	Single Pass	200	microns
	Stored Beam (4 kHz BW)	25	microns
Accuracy:	Single Pass	500	microns rms
	Stored Beam (4 kHz BW)	200	microns rms

X-ray Position Monitors

Accuracy:	150	microns
Resolution:	1	micron
Bandwidth:	200	Hz

3.3.2 Magnet rms Alignment Tolerances - Short Range (component to component across 1 to 2 sectors)

	Radial (x)	Vertical (y)	Roll (θ)
Dipole	0.2 mm	0.2 mm	0.5 mrad
Quadrupole	0.2 mm	0.2 mm	0.5 mrad
Sextupole	0.2 mm	0.2 mm	0.5 mrad
H/V Correctors	0.5 mm	0.5 mm	1.0 mrad
Skew Quads	0.5 mm	0.5 mm	1.0 mrad

3.3.3 Maximum Allowable Misalignment Tolerances - Short Range

	Radial (x)	Vertical (y)	Roll (θ)
Girders in tunnel	0.2 mm	0.2 mm	--
Quads on same girder	0.1 mm	0.1 mm	0.5 mrad
Sext. on same girder	0.1 mm	0.1 mm	0.5 mrad
Dipole on girder	0.1 mm	0.1 mm	0.5 mrad

3.3.4 Global Alignment Tolerances

	Radial (x)	Vertical (y)	Longitudinal (s)
Quadrupole	5 mm	5 mm	--
Sextupole	5 mm	5 mm	--
Circumference	--	--	20 mm

3.3.5 Survey Tolerances

	Radial (x)	Vertical (y)
BPMs relative to adjacent sextupole or quadrupole	0.1 mm	0.1 mm
SRVC exit slot at crotch relative to front end x-ray BPMs (S2 and S4)	--	0.15 mm
S2 wedge absorber relative to front-end x-ray BPMs	0.15 mm	--
S2 crotch absorber relative to front-end x-ray BPMs	0.15 mm	--

3.3.6 Magnetic Field Quality

Field errors (rms) in dipole magnets:

$$BL = B_0L \sum_{n=0}^{3} (b_n + ia_n)(x + iy)^n$$

Normal (b_n) Component	Field Error		Fractional Error (at 2.5 cm)	
b_0	5×10^{-4}		5×10^{-4}	T-m
b_1	1×10^{-4}	cm^{-1}	2.5×10^{-4}	T
b_2	5×10^{-5}	cm^{-2}	3.1×10^{-4}	T / m
b_3	1×10^{-5}	cm^{-3}	1.6×10^{-4}	T / m^2

Skew (a_n) Component	Field Error		Fractional Error (at 2.5 cm)	
a_0	5×10^{-4}		5×10^{-4}	T-m
a_1	1×10^{-4}	cm^{-1}	2.5×10^{-4}	T
a_2	5×10^{-5}	cm^{-2}	3.1×10^{-4}	T / m
a_3	1×10^{-5}	cm^{-3}	1.6×10^{-4}	T / m^2

Field errors (rms) in quadrupole magnets:

$$BL = B_0L \sum_{n=1}^{3} (b_n + ia_n)(x + iy)^n$$

Normal (b_n) Component	Field Error		Fractional Error (at 2.5 cm)	
b_1	5×10^{-4}	cm^{-1}	5×10^{-4}	T
b_2	1×10^{-4}	cm^{-2}	2.5×10^{-4}	T / m
b_3	5×10^{-5}	cm^{-3}	3.1×10^{-4}	T / m^2

Skew (a_n) Component	Field Error		Fractional Error (at 2.5 cm)	
a_1	5×10^{-4}	cm^{-1}	5×10^{-4}	T
a_2	1×10^{-4}	cm^{-2}	2.5×10^{-4}	T / m
a_3	5×10^{-5}	cm^{-3}	3.1×10^{-4}	T / m^2

Field errors (rms) in sextupole magnets:

$$BL = B_0L \sum_{n=2}^{3} (b_n + ia_n)(x + iy)^n$$

Normal (b_n) Component	Field Error		Fractional Error (at 2.5 cm)	
b_2	5×10^{-4}	cm^{-2}	5×10^{-4}	T / m
b_3	5×10^{-5}	cm^{-3}	1.25×10^{-4}	T / m^2

Skew (a_n) Component	Field Error		Fractional Error (at 2.5 cm)	
a_2	1×10^{-3}	cm^{-2}	1×10^{-3}	T / m
a_3	5×10^{-5}	cm^{-3}	1.25×10^{-4}	T / m^2

Correctors are $\Delta B / B$ less than 0.8×10^{-3} inside 3.2-mm radius.

3.3.7 Insertion Devices

3.3.7.1 Performance Requirements

(source: Technical Specifications for Undulator A, Doc. No. 41010101-00002)

	Normal	Skew
First field integral (maximum variation with gap)	100 Gauss-cm	50 Gauss-cm
Second field integral (maximum variation with gap)	100 000 Gauss-cm^2	100 000 Gauss-cm^2
Quadrupole (n=1)	50 Gauss	50 Gauss
Sextupole (n=2)	200 Gauss/cm	100 Gauss/cm
Octupole (n=3)	300 Gauss/cm^2	50 Gauss/cm^2
with the following definitions:		
first normal field integral		$\int B_y \, dz$
first skew field integral		$\int B_x \, dz$
second normal field integral		$\int_{-\infty}^{\infty} dz \int_{-\infty}^{z} dz' B_y(z')$
second skew field integral		$\int_{-\infty}^{\infty} dz \int_{-\infty}^{z} dz' B_x(z')$

where ∞ is well outside the undulator and the earth's field contribution is subtracted. The definition of the normal (b_n) and the skew (a_n) multipoles is

$$\int dz (B_y + iB_x) = \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n$$

where z is the direction parallel to the particle beam,
y is the direction normal to the plane of the design orbit, and
x points radially outward from the center of the storage ring.

3.3.7.2 ID Vacuum Chamber

Aperture:	12.00±0.25	mm (Phase I)
Straightness:	75	microns
Aperture:	8.00±0.25	mm (Phase II)
Straightness:	75	microns

3.3.7.3 Alignment

(source: Installation and Alignment of the ID Vacuum Chamber, Procedure No. XF-IP3)

± 75 microns in x, ± 75 microns in y, and ± 750 microns in z

3.3.7.4 Survey

± 150 microns relative to adjacent quadrupoles

3.3.7.5 Insertion Device RFBPMs

Accuracy relative to ID center line:	150	microns
Resolution:	8	microns
Long term stability:	30	microns

3.3.8 Power Supplies DC

	Dip.	Quad.	Sext.	Trim	HCorr	VCorr	SQ
Stability (ppm)	30	30	300	300	300	300	300
Reproducibility (ppm)	50	100	600	600	600	600	600
Current ripple (ppm)	400	800	2000	10000	1000	1000	1000
Tracking error (ppm)	100	200	700	700	700	700	700
Resolution (bits)	16	16	13	13	16	16	13

3.3.9 Injection Power Supplies

	Thin Septum	Thick Septum	Pulsed Bumpers
Reproducibility (ppm)	100	100	100
Current ripple (ppm)	200	200	200
Tracking error (ppm)	500	500	500
Resolution (bits)	14	14	14

3.4 Storage Ring Injection System

The 7-GeV beam bunches from many pulses of the injector synchrotron are injected into pre-designed rf buckets around the storage ring orbit. At 3.6×10^{10} positrons / bunch 60 bunches will give the nominal design current of 100 mA. Injection is accomplished by using septum and bumper magnets.

Parameters of the storage ring injection septa and magnets are given below.

Pulsed septum, thin

Number	1	
Minimum septum thickness	2	mm
Physical length	1.06	m
Effective length	1.05	m
Gap height	20	mm
Gap width	34	mm
Peak field	0.73	T
Peak supply current	11.74	kA
Peak power	62	kW
Power	0.042	kW
Pulse width (1.5 kHz half-sine)	333	μ

Pulsed septum, thick

Number	1	
Minimum septum thickness	30	mm
Physical length	1.79	m
Effective length	1.75	m
Gap height	30	mm
Gap width	40	mm
Field at 7 GeV	1.08	T
Peak supply current	0.66	kA
Peak power	80	kW
Average power	0.797	kW

Bumper magnets

Number	4	
Magnetic length	0.5	m
Beam bending angle	1.782	mrad
Gap height	5.5	cm
Gap width	11.0	cm
Field	915	Gauss
Peak current	4	kA
Total pulse width	3.5	μs

3.5 Storage Ring Vacuum System

In order that the beam can circulate with a lifetime of many hours, a vacuum of better than one nanoTorr is required. A bakeable aluminum vacuum chamber is used. To minimize outgassing by synchrotron radiation, the cross section of the chamber is designed to let out the desired synchrotron radiation and catch all unwanted synchrotron radiation on localized and heavily pumped absorbers. The chamber is furnished with distributed and lumped high-vacuum pumps.

Parameters of the vacuum system are given below.

Vacuum chamber

Material	6063 T5 Aluminum	
Horizontal aperture (beam chamber)	85	mm
Vertical aperture (beam chamber)	42	mm
Minimum vertical aperture in undulator	8	mm
Vacuum pressure (Avg. after 100 A·hour)	1	nTorr
Chamber wall thickness (in beam position chamber area)	12	mm
Positron beam lifetime	>10	hours

3.6 Storage Ring Radiofrequency System

The energy lost by the positron beam into synchrotron radiation is replenished by a 352-MHz radiofrequency system consisting of 16 cavities and associated power suppies installed around the ring circumference.

Parameters of the rf system are given below.

Harmonic number	1296	
RF frequency	351.927	MHz
Peak voltage	9.500	MV
Number of cavities	16	

Cavity parameters		
Max voltage (estimated)	1.00	MV
Shunt resistance	5.60	MΩ
Max power	89.2	KW
Quality factor, Q	8.6	10^3

Operating values	7 GeV 100 mA	7 GeV 300 mA	7.5 GeV 200 mA	
Voltage	9.5	9.5	12.0	MV
Voltage per cavity	593.8	593.8	750.0	kV
Power per cavity	31.5	31.5	50.2	kW
Total power	503.7	503.7	804.0	kW
Beam power per cavity	43.1	129.3	113.7	kW
Sum	74.6	160.8	163.9	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	1.32	2.85	2.90	MW

3dB bandwidth of cavity alone = 7.23 kHz

3.7 Beam Diagnostics System

A large number of beam monitors which measure beam intensity, position, and profile are installed around the circumference of the ring. Signals from these monitors are processed and transmitted to the controls system.

Types, characteristics, and numbers of beam monitors are given below.

4-button standard pickups	360	
Accuracy	200	μm
Sensitivity	0.16	$\mu m / \sqrt{Hz}$
4-button insertion-devices pickups	2 × (number of IDs)	
Accuracy	200	μm
Sensitivity	0.10	$\mu m / \sqrt{Hz}$
Current transformers	2	
Precision (5 μA standard resolution)	1	
High speed	1	
Photon monitoring beamlines	2	
Including: UV imaging station		
X-ray pinhole camera		
Streak camera		
RF-drive electrodes and amplifiers	2	sets
	(1 set = 4 electrodes, 2 amplifiers)	
Stripline pickups	2	sets
	(1 set = 4 electrodes)	
Vertical pinger	1	
Loss monitors	10, 5 detectors, multiplexed	
Fluorescent screens	10	
Horizontal beam dump scrapers	2	
(Inboard, single jaw)		
Horizontal window frame scraper	1	
Vertical scraper pairs (top and bottom)	2	

4.0 EXPERIMENTAL FACILITIES SYSTEM

The experimental facilities will include construction of a set of insertion devices, front ends of beamlines, first optics, and complete beamlines including experimental stations.

4.1 Insertion Devices

4.1.1 Undulator A Parameters and Specifications

Magnet material	Nd-Fe-B	
Pole material	Vanadium permendur	
Undulator period, λ_u	3.3	cm
Number of periods, N[1]	72	
Undulator length, L	2.4	m
Minimum gap	10.5	mm
Maximum gap taper[2]	2	mrad
Deflection parameter[3], K_{eff}	2.57	
Peak deflection parameter[3], K_{peak}	2.62	
Maximum effective field[3], B_{eff}	0.835	T
Maximum peak field[3], B_{peak}	0.849	T
First harmonic energy[3], E_1	3.2	keV
Rms peak magnetic field error[4]	< 0.5	%
Rms phase error[4]	< 8	(°)

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[1] The number of periods is kept at 70 for all spectral calculations, so the endpoles were omitted. For power calculations, a conservative value of 72 periods was used.

[2] Specified value; opens at downstream end.

[3] Evaluated at minimum gap of 10.5 mm.

[4] Specified at a gap of 11.5 mm.

4.1.2 Wiggler A Parameters and Specifications

Parameters are for max. magnetic field of	1.0	0.3	T
Undulator period, λ_u	8.5	8.5	cm
Number of periods, N	28	28	
Device length, L	2.4	2.4	m
Approximate magnetic gap	1.9	4.6	cm
Deflection parameter, K	7.9	2.4	
First harmonic energy, E_1	0.17	1.4	keV
Critical energy, E_c	32.6	9.8	keV
Parameters of the photon source:			
Total photon source size, rms			
Horizontal, Σ_x		325 *	µm
Vertical, Σ_y		86 *	µm
Total photon source divergence, rms			
Horizontal, $\Sigma_{x'}$		30.0 *	µrad
Vertical, $\Sigma_{y'}$		21.2 *	µrad
Total power	7.4	0.67	kW
Peak power density	73	22	kW / m · rad^2
Peak normal heat flux at 30 m	81	24	W / mm^2

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* Quantities evaluated at first harmonic energy of 1.4 keV.