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AN OVERVIEW OF THE ADVANCED PHOTON SOURCE*

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ABSTRACT

The need for dedicated synchrotron radiation facilities based on insertion devices and a low emittance storage-ring has been recognized for many years. A facility optimized to produce x-rays from 1 to 100 keV is expected to dramatically enhance research capabilities in the areas of condense matter physics, material sciences, chemical sciences, and biological sciences, in addition to contributing in a major way to the industrial research. This goal will be accomplished by the construction of the Advanced Photon Source (APS) facility consisting of a 7-GeV positron storage-ring with 100 mA current and 35 straight-sections to accommodate insertion devices. The ring energy has been chosen so that a single undulator will provide radiation from 4 to 40 keV (using the first and the third harmonics) with 0.2% bandwidth. The low emittance of 7 X 10^{-9} rad.m will provide hard-x-ray undulator radiation with very high brilliance (~ 10^{18} to 10^{19} photons/(s mm^2 $mrad^2$). [Construction is expected to begin in 1989 at Argonne National Laboratory.] This overview will mainly address the facility from the users point-of-view.

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I. INTRODUCTION

During the past decade, electron storage rings have been built specifically dedicated to producing low emittance synchrotron radiation and designed primarily to extract beam lines from the storage-ring bending-magnets. The principal index of performance for these sources is the integrated photon flux.

In the next generation photon sources, the spectral properties of the photon beams are enhanced, firstly through the use of special magnetic devices such as "undulator" and "wigglers", and secondly, through the further reduction of the emittance of the particle (electron or positron) beam circulating through the storage ring. The design of the 7-GeV Advanced Photon Source (APS) includes these features.

The special magnetic devices, also known as the insertion devices, are placed in the straight sections (or the insertions) of a storage ring. Unlike bending magnets, these sources provide complete flexibility to tailor the characteristics of the radiation to meet the needs of the experiment. The APS, for example, will provide tunable pseudo-monochromatic radiation from the undulators with energies from 1 keV to 40 keV, and white radiation from the wigglers to over 100 keV.

During the past four years, many national advisory panels have made their highest-priority recommendation the construction of a hard x-ray source with features provided by the APS [1-5]. The unprecedented brilliance of the hard x-rays from the APS is expected to revolutionize many areas of basic research, industrial research, biological and medical research, and defense-related research; the unique properties of the radiation from the APS undulator will provide new possibilities of imaging at a sub-micron level, perhaps leading the way to holographic imaging of the molecules and atoms in the future sources. The APS will be operated as a national user facility serving the entire U.S. x-ray research community of several thousand users, with about 300 scientists taking data at any given time.

The present paper gives a brief overview of the 7-GeV APS from a user point-of-view. A discussion of the storage ring and other accelerator component design have been presented earlier [6].

II. INSERTION DEVICES ON THE APS

The distinction between the two types of IDs - wigglers and undulators - is based on the value of the so-called deflection parameter K given by

$$K = 0.934\ B_o\ \lambda_o \qquad (1)$$

where B_o is the peak magnetic field (Tesla) in the device and λ_o is the spatial period (cm) of the magnetic structure.

When K is small (< 4), the device is called an undulator. The radiation from various poles of an undulator interferes constructively resulting in a spectrum consisting of sharp peaks at harmonics of the first-harmonic energy, E_1. This energy is given by

$$E_1(\text{keV}) = \frac{0.95\ E^2\ (\text{GeV}^2)}{\lambda_0(\text{cm})\ (1 + K^2/2)} \qquad (2)$$

where E is the positron energy. The following are important features of APS undulators:

- The undulators on the APS ring to be built with the available Nd-Fe-B hybrid magnet technology will deliver first-harmonic radiation with energies ranging from a few hundred eV to 20 keV. The typical on-axis angle integrated brilliance for the fundamental radiation ranges from 10^{18} to 10^{19} photons/s/0.1%BW/mrad^2/mm^2.

- A fully tunable undulator with 3.3 cm period on the APS will deliver radiation from 4 to 14 keV in the first-harmonic and from 12 to 42 keV in the third-harmonic. The energy tunability is achieved by varying the undulator gap from 1.0 cm to about 2.5 cm [7].

- For applications needing only the high-energy undulator fundamental radiation, device with a period of 2.3 cm will be tunable from 13.5 to 20 keV through gap variation.

- The phase space dimensions of the photon source is nearly equal to that of the positron beam for the hard x-rays delivered by the APS undulators.

- The vacuum chambers for the undulators will permit a minimum gap of either 1.4 cm or 1.0 cm. The larger chamber will be used during the initial operational period of the APS.

When K is large (>10), the device is called a wiggler. The radiation peaks from higher harmonics of a wiggler tend to smooth out due to smearing effects of the positron-beam emittance and energy spread. This results in a smooth spectrum similar to that from a bending magnet (BM). The intensity of the radiation from a wiggler with N periods is approximately equal to an incoherent sum of intensities from 2N poles. One can also increase or decrease the critical energy of the photons from a wiggler by proper choice of B_o, while maintaining a large value of K given by Eq. (1). The photon critical energy for the APS operated at 7 GeV is given by

$$E_c \text{ (keV)} = 32.59 \, B_o, \tag{3}$$

and the horizontal opening angle of the radiation is given by

$$\theta_H = \pm \, 73{*}K \, \mu\text{rad}. \tag{4}$$

Several important features of the APS wigglers deserve mention:

- They will rarely require magnetic fields produced by superconducting magnets. The field provided either by the Nd-Fe-B hydrid magnets or by electromagnets is adequate to obtain large K values and nearly smooth photon energy spectrum, up to the highest photon energies generally useful for x-ray research.

- The value of θ_H (Eq. (4)) for the APS wigglers is approximately ± 1 mrad. Hence, the APS wigglers deliver very high brightness hard x-rays compared with those on the low-energy storage rings.

- The availability of 6m long straight sections, is suitable for long-period wigglers designed to provide radiation of low critical energy. These devices (with $K \sim 10$) operate with $\beta \approx 10$ m and hence provide a low divergence photon beam. These high-brightness wigglers are unique to the present design and are essential for many research programs.

- In many investigations, there is a need for radiation with linear polarization along the vertical axis. A design of such a high-brightness wiggler with hybrid magnet configuration has been completed.

The IDs with $4 < K < 10$ produce energy spectra with features that are intermediate between those of undulators and wigglers. Devices capable of delivering hard x-rays from the undulator to the wiggler regime through a gap variation have been designed for the APS.

In Table 1, a set of optimized parameters for a typical wiggler and an undulator for the 7-GeV APS are presented. Their energy spectra are shown in Fig. 1. The undulator curve represents the envelope of the peak of the first- and third-harmonic energy spectra when the undulator described in Table 1 is tuned by varying its gap from 1 cm to 2.8 cms. A single undulator thus provides high-brilliance-radiation from roughly 4 to 40 keV using the first and the third harmonics. A comparison has been made of the radiation brilliance from other important sources.

III. PHOTON SOURCE DIMENSIONS

The spectral brilliance, the quantity which is optimized in the APS design, is the spectral intensity emitted in the unit phase-space volume of the radiation field. Hence, it is essential to minimize the phase-space volume. For the APS in the hard x-ray range, the phase-space volume of the photon field is totally determined by the positron phase-space volume. In terms of the betratron functions, β_x and β_y, in the horizontal and the vertical directions, the rms Gaussian widths and divergences of the positron beam are given by

$$\sigma_i = \sqrt{\varepsilon_i \beta_i} \; ; \quad \sigma_i' = \sqrt{\varepsilon_i / \beta_i} \; ; \quad i = x,y \qquad (5)$$

where $\varepsilon_x = 7.3 \mathrm{x} 10^{-9}$ rad.m and $\varepsilon_y = 7.3 \mathrm{x} 10^{-10}$ rad.m are the horizontal and vertical emittances. The phase-space volume is given by $S = 4\pi\sigma_x\sigma_y\sigma_x'\sigma_y'$.

The source size, however, can be altered by changing the value of betatron functions. Their values can be optimized for the best performance of the lattice, but it is advantageous to have certain flexibility in choosing their values in the dispersion-free straight sections. Thus having small values of betatron functions will produce small physical size of the source but large divergence. Small betratron values are ideal for wigglers. In the undulator straight sections, small values of the betatron functions will produce broad energy peaks and higher intensity in the region of the higher harmonics. Such a spectral distribution is useful for certain applications, such as anomalous scattering. On the other hand, many investigations demand small angular divergence of the undulator beam and sharper peaks in the energy spectrum. For these cases, it is appropriate to use larger values of betatron function. It should be pointed out that because of smaller emittance of the lattice in the vertical direction, the vertical angular divergence is usually small. Hence, it is adequate to increase the value of β_x to achieve small divergence photon beams.

In Table 2, some typical values of the betatron functions that are possible in the various parts of the APS lattice are given along with the resulting source dimensions.

IV. LAYOUT OF STORAGE-RING AND EXPERIMENTAL FACILITIES

In Fig. 2, the present layout of the storage-ring and other accelerator components is shown. A 200 keV linear accelerator produces 3 amp electron pulses of 16.5 nsec width. This beam is converted to a beam of 25 mA positron pulses using a tungsten target and then accelerated to 450 MeV. The positrons are further accelerated to 7-GeV in a booster synchrotron 367 m circumference. The accelerated positrons are then injected into pre-defined number of the 1248 available rf bunches in the storage ring. Typical number of bunches is expected to be about 40-60 to store 100 mA current. The parameters of the storage ring are given in Table 3. One of the 40 sectors of the storage-ring is shown in Fig. 3 to indicate the location of the insertion device and bending magnet sources. Note that although there are 80 bending magnets in this lattice, only 35 will be available for extracting photon beams.

The photon beams from the IDs located in the 34 available straight sections emerge through the beam ports in the vacuum chamber at the downstream ends of the dipoles. The beams travel in vacuum pipes out of the storage ring shielding tunnel into the experimental hall. Each beam is generally manipulated a number of times with various types of optical elements before reaching the sample for the experiment. The beam lines and experiments, some of which may extend more than 80 m in length, occupy the annular floor space around the storage ring. To accommodate 80-m beams, the radial width of the experiment hall is about 27 m. It is expected that some extra-long beam lines will extend beyond the outside wall of the experiment hall and will be housed in special extended enclosures. A partial layout of the experiment building showing the photon beams is given in Fig. 4.

Generally speaking, the photon beam line consists of four functional sections. The first section is the ID on the storage ring straight section that provides the radiation source. In some cases, the bending magnets deliver the radiation.

The second section, immediately outside the storage ring but still inside the concrete shielding tunnel, is the front-end section. This section contains safety shutters, masks, and other components to define the emerging x-ray beam.

The third section contains hard x-ray optics. In a majority of experiments, this assembly delivers a focused monochromatic beam of x-rays. The section includes crystals and/or mirror optics that are designed to handle the radiation power loads and provide the monochromatization required for the specific investigation.

The monochromatic x-rays are delivered to an experimental station that forms the fourth section. This station contains the sample under investigation and detectors and/or analyzers to detect and characterize the scattering, imaging, and absorption processes.

Most of the beam lines, including the experimental setups, will be shorter than 80 m and can be housed in the experimental hall. The entire 27-m-wide annular experiment hall is serviced by 5-ton overhead cranes and by several clusters of offices, laboratories, clean rooms, experiment staging rooms, etc., distributed along the periphery.

Number of specialized beam line facilities will be built at the APS. One example is a special beam line facility for coronary angiography studies. In view of the encouraging results of recent angiography tests at Stanford using synchrotron radiation, further research using a dedicated beam at the APS will be of unique value for developing these techniques and for extending the use of the synchrotron radiation into new realms of medical examination and diagnosis.

Another example concerns specialized facilities for classified research. In view of the DOE intent that classified research be carried out at the APS if the need arises, we have considered various means for carrying out such work effectively, with minimal impact on other activities at the APS.

The central laboratory/office building is a three-story building with ~180,000 ft^2 total floor area (exclusive of auditorium), located adjacent to the experiment hall as shown in Fig. 2. The central laboratory/office building houses the regular operations staff, control room, clean room, staging areas for major component assemblies, computer facilities, auditorium, library, machine shops, and various other service in addition to users. In addition, there are laboratory/office modules which will be available for the users located around the outer perimeter of the experimental hall (see Fig. 2). The detailed layout of this user area is now being finalized.

Convenient housing for the many outside users of the source will be an important component of the overall facility. Current predictions of user numbers indicate an initial need for a 240-bed complex. It would be highly desirable to have this housing completed approximately one year before the source is user-ready to be available to research groups constructing beam lines prior to commissioning.

ACKNOWLEDGMENTS

We would like to thank the entire staff of the Advanced Photon Source which has contributed to the design discussed in this paper.

TABLE 1

Optimized Parameters of a Nd-Fe-B Hybrid Insertion Devices with the APS

Parameters	Undulator	Wiggler
Periods, λ_o (cm)	3.3	15.0
Magnet Gap Range, G (cm)	1.0 - 2.8	3.7
Peak Field Range on Axis, B_o (T)	0.78 to 0.21	1.0
K value range	2.4 to 0.65	14
Length of Straight Section (m)	6.0	6.0
Minimum Length of Transition Section (m)	0.4	0.4
Maximum Length Available for the Insertion Device (m)	5.2	5.2
Maximum Undulator Periods, N	162	10
Critical Energy (keV)	*	32.6

*Tunability range given in the text.

TABLE 2

Typical values of betratron functions in the different parts of the lattice and the dimensions of different sources

Source	β_x m	β_y m	σ_x µm	σ_y µm	σ'_x µrad	σ'_y µrad
Bending Magnet	5.5	13.0	200	97	36	8
Undulator 1	13.0	10.0	308	85	24	9
Undulator 2	20.0	5.0	382	60	19	12
Wiggler	13.0	10.0	308	85	24	9

REFERENCES

1. P. Eisenberger and M. L. Knotek, Chairmen, "Planning Study for Advanced National Synchrotron-Radiation Facilities," Sandia National Laboratory Report (March 1984).

2. F. Seitz and D. Eastman, Chairmen, "Major Facilities for Materials Research and Related Disciplines," National Academy of Science, Washington, D.C. (1984).

3. W. Brinkman, Chairmen, "Physics Throughout the 1990's: An Overview," NRC Report, National Academy of Sciences, Washington, D.C. (1986).

4. F. Stehli, Chairman, "Review of the National Research Council Report on Major Facilities for Materials Research," Energy Research Advisory Board Subcommittee, DOE (1986).

5. B. Ancker-Johnson, Chairperson, "Review of the National Research Council Report on Physics through the 1990's," Energy Research Advisory Board Subcommittee, DOE (1987).

6. Y. Cho, Particle Accelerator Conference, Washington, D.C., March 16-19, 1987.

7. P. J. Viccaro and G. K. Shenoy, presented at this conference.

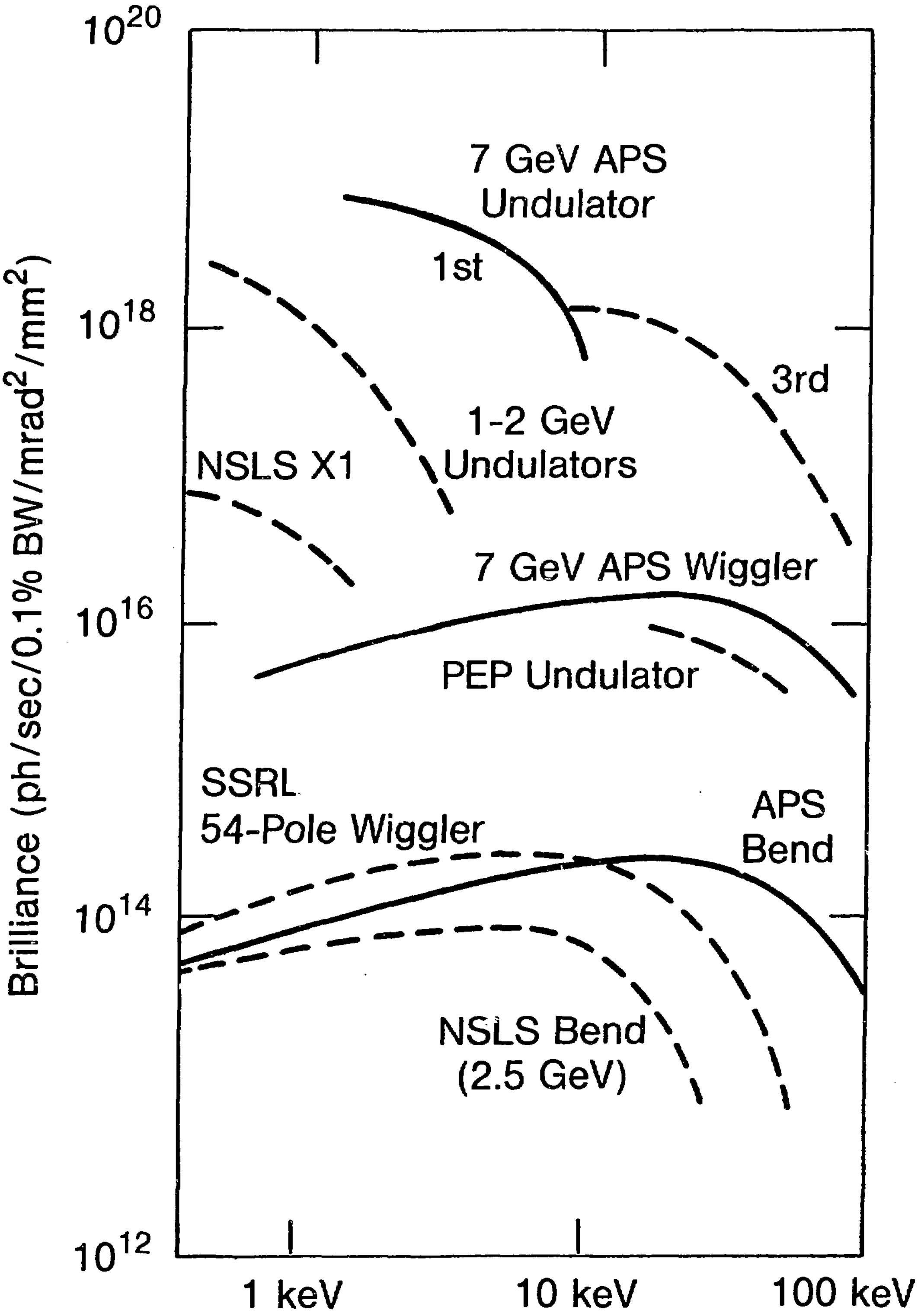
FIGURE CAPTIONS

Fig. 1 Brilliance of various sources as a function of energy. The 7-GeV APS undulator is the 3.3 cm period device discussed in the text. The curve represents the envelope of the first and the third harmonic energies tunable by the gap variation. Similar curves for the undulators on the 1-2 GeV Synchrotron Radiation Source at Berkeley, X-1 undulator on the National Synchrotron Light Source (NSLS) and for the 7.7 cm period undulator on PEP ring (14.5 GeV) at Stanford are also shown.

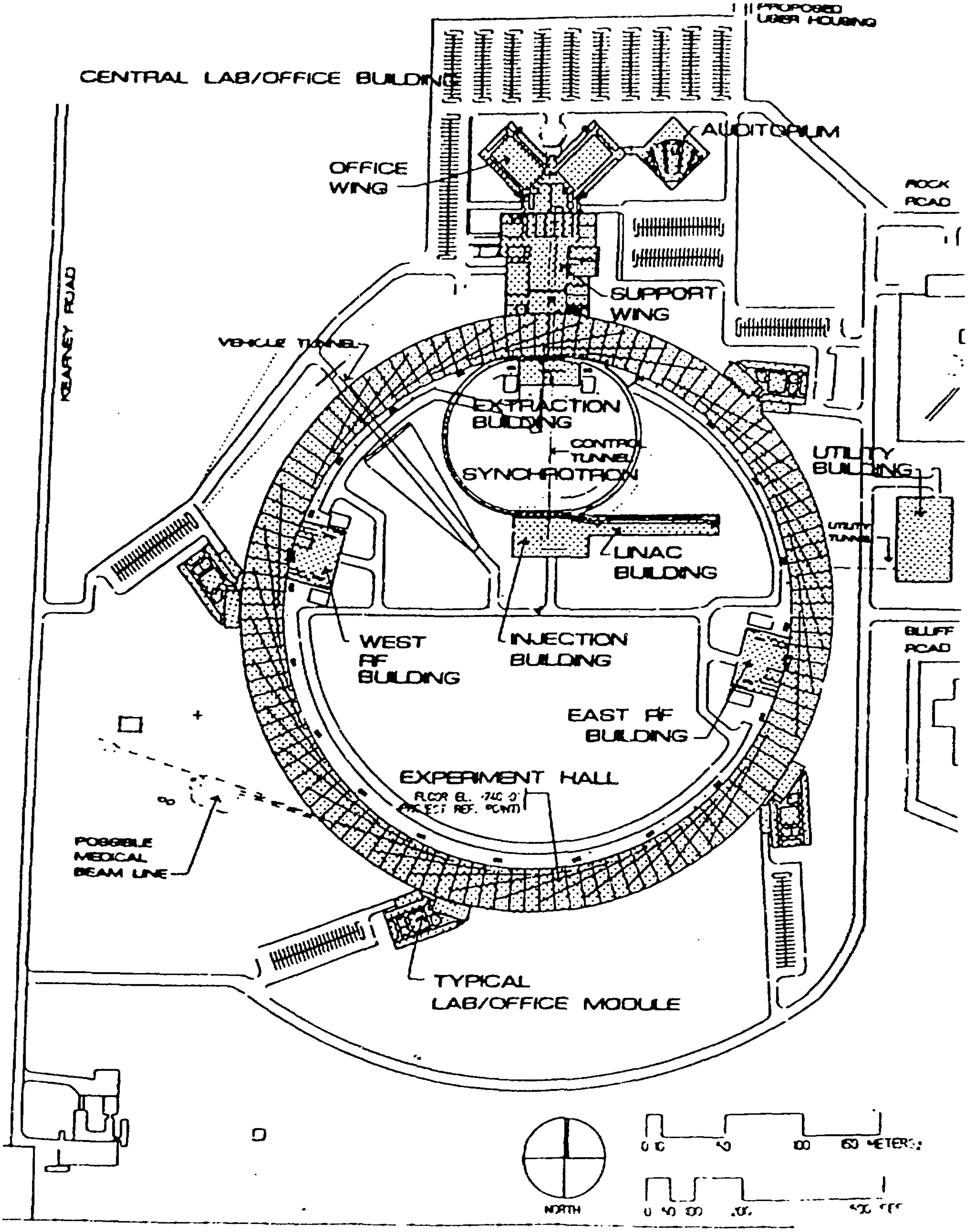
Fig. 2 Layout of the Advanced Photon Source showing various conventional construction.

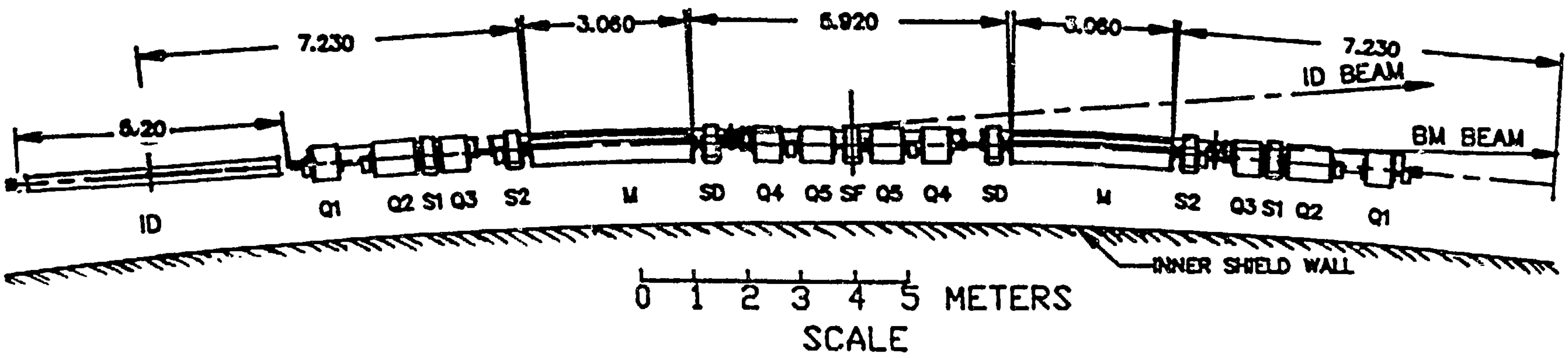
Fig. 3 One cell of the storage ring magnet lattice showing the location of the insertion device and bending magnet sources.

Fig. 4 Layout of typical beamlines in a part of the storage ring experimental hall. These beamlines are defined for a possible set of investigations and use undulator, wiggler and bending magnet sources.

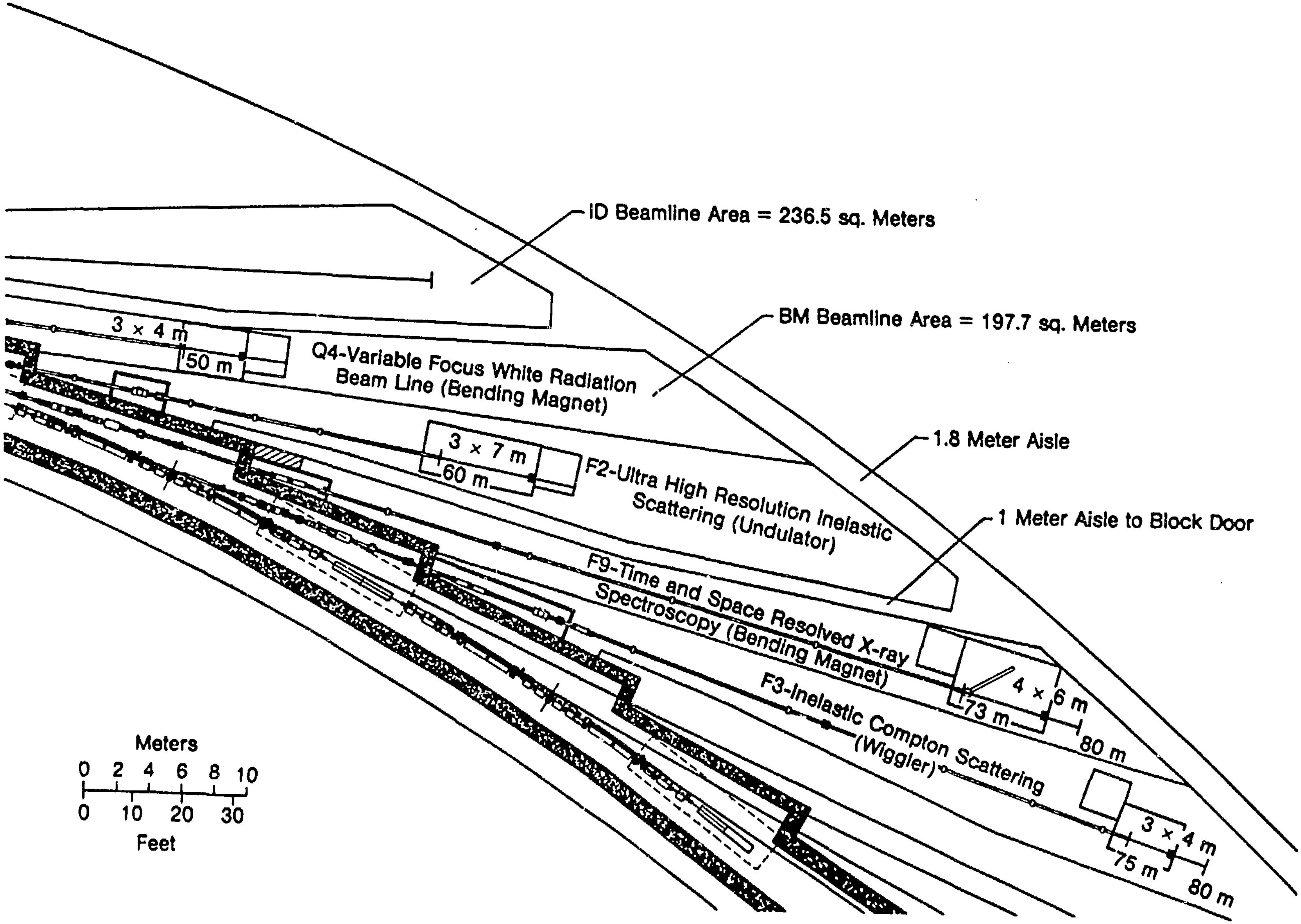


10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
Brilliance (ph/sec/0.1% BW/mrad^2/mm^2)
1 keV
10 keV
100 keV
7 GeV APS Undulator
1st
3rd
1-2 GeV Undulators
NSLS X1
7 GeV APS Wiggler
PEP Undulator
SSRL 54-Pole Wiggler
APS Bend
NSLS Bend (2.5 GeV)


PROPOSED USER HOUSING
CENTRAL LAB/OFFICE BUILDING
AUDITORIUM
OFFICE WING
ROCK ROAD
SUPPORT WING
KEARNEY ROAD
VEHICLE TUNNEL
EXTRACTION BUILDING
CONTROL TUNNEL
SYNCHROTRON
UTILITY BUILDING
UTILITY TUNNEL
LINAC BUILDING
BLUFF ROAD
WEST RF BUILDING
INJECTION BUILDING
EAST RF BUILDING
EXPERIMENT HALL
FLOOR EL. 740.0' PROJECT REF. POINT
POSSIBLE MEDICAL BEAM LINE
TYPICAL LAB/OFFICE MODULE
NORTH
0 10 50 100 150 METERS
0 50 100 200 500 FEET



7.230
3.060
6.920
3.060
7.230
6.20
ID BEAM
BM BEAM
ID
Q1
Q2
S1
Q3
S2
M
SD
Q4
Q5
SF
Q5
Q4
SD
M
S2
Q3
S1
Q2
Q1
INNER SHIELD WALL
0
1
2
3
4
5
METERS
SCALE


ID Beamline Area = 236.5 sq. Meters
BM Beamline Area = 197.7 sq. Meters
1.8 Meter Aisle
1 Meter Aisle to Block Door
3 × 4 m
50 m
Q4-Variable Focus White Radiation Beam Line (Bending Magnet)
3 × 7 m
60 m
F2-Ultra High Resolution Inelastic Scattering (Undulator)
F9-Time and Space Resolved X-ray Spectroscopy (Bending Magnet)
4 × 6 m
73 m
80 m
F3-Inelastic Compton Scattering (Wiggler)
3 × 4 m
75 m
80 m
Meters
0 2 4 6 8 10
0 10 20 30
Feet