CONF-9405365--1
ANL/OTD-APS/CP--89542

Accelerator Developments Since the ZGS by ZGS People

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I. INTRODUCTION

The ZGS was a facility, as well as an organization, where people got together to pursue a common goal of doing exciting science of the day. In this note, we describe notable events related to accelerators and accelerator people since the closing of the ZGS program some 15 years ago. Many of the same ZGS people have been carrying out the state-of-the art accelerator work around the Laboratory with the same dedication that characterized their work in the earlier days.

First we describe how the activities were re-organized after the closing of the ZGS, the migration of people, and the organizational evolution since that time. Doing this shows the similarity between the birth of the ZGS and the birth of the Advanced Photon Source (APS). Then, some of the accelerator work by the former ZGS people are described. These include: 1) Intense Pulsed Neutron Source (IPNS), 2) GeV Electron Microtron (GEM), 3) Wake Field Accelerator Test Facility, 4) Advanced Photon Source, and 5) IPNS Upgrade.

II. PEOPLE

We like to high-light the activities of the people since the closing of the ZGS. The people work in an organization, which we learn how to work together. So it may be worthwhile to review how the ZGS organization evolved starting from 1956, and how it stands today. There was an accelerator group under the leadership of J. J. Livingood in the Physics Division from 1954 to 1956. In 1956, this group became the Particle Accelerator Division (PAD) to work on what had become the ZGS. In 1958, an Associate Laboratory Directorship (ALD) for High Energy Physics was created and the High Energy Physics Division branched out from PAD in 1959. During the peak years of the ZGS(1967), PAD was further divided to an Accelerator Division (AD) and a High Energy Facilities Division (HEF). As the ZGS operations progressed into a mature phase, AD and HEF were combined again to form Accelerator Research Facilities Division (ARF) in 1973.

After closing the ZGS in September 1979, the ALD-HEP position was discontinued in 1980, and both ARF and HEP divisions were led by the ALD-Physical Research. In April 1982, the ARF Division was dissolved, and people were moved to other Divisions such as IPNS, Physics Division, HEP Division and ET (Electromagnetic Technology) Group.

The ZGS Operations Group under leadership of C. Potts and F. Brumwell became IPNS Operations Group. E. Crosbie, T. Khoe, R. Kustom, E. Colton and H. Takeda went to the Physics Division to work on a multi-GeV continuous beam electron microtron (GEM) the design work of which is described later. Crosbie, Khoe and Kustom returned to the HEP Division in 1984 to join the APS Project.

People returning from the ARF Division to HEP were Y. Cho, S. Kramer and J. Simpson who had started their careers in the HEP Division. Simpson and Kramer were members of P-bar Group working on the anti-proton project for Fermilab. After completion of the P-bar work, Simpson and his group have been carrying out very interesting work on new concepts of acceleration which is discussed later. Cho started the APS Project in 1983 from the HEP Division, as described in some detail below.

A large accelerator facility like the ZGS has a unique group of experts on electromagnetics and mechanical engineering to provide magnets and their supports, power supplies, vacuum chamber systems, etc. We had such a group under leadership of W. Praeg, and during the post-ZGS era, this group was called ET (Electromagnetic Technology) Group, and worked on various projects throughout the Laboratory including the GEM project. In 1984, this group joined the APS Project and become the key players in that activity.

Birth of the APS: Starting from the summer of 1983, I was on-loan to the University of Wisconsin-Madison to work on the university's synchrotron radiation source which was being commissioned but having difficulties meeting its performance goals. In November of that year, while in Madison, I obtained a copy of letter report from the Eisenberg-Knotek Committee being circulated amongst the synchrotron radiation community in the US. The Committee was chartered by the Office of Basic Energy Science of the US DOE to recommend priorities for the Nation's synchrotron radiation facilities. The Committee advocated that the first priority of the DOE synchrotron facility should be the construction of 6 GeV accelerator facility to produce very bright hard x-ray beams for materials research. With a copy of this letter report on hand, I requested Laboratory program development funds to support a group to design and construct a 6 GeV accelerator facility.

To that time, utilization of synchrotron radiation in research was not a strong point of the ANL program, but, in spite of this, the Laboratory management decided to give a chance to a group of people to compete with other proponents. The funding support for FY 1984 was some $400K.

Former ZGS people who had returned to the HEP Division or participated from other ANL Divisions were: Y. Cho and S. Kramer from HEP Division, E. Crosbie, T. Khoe and R. Kustom from PHY Division, W. Praeg, S. Kim, M. Knott, D. McGhee, J. Moenich (who un-retired to work on the APS), K. Thompson, and R. Wehrle from ET Group, A. Rauchas from IPNS Division, R. Bouie from PFS Division, L. Genes and D. Hillis from EES Division. The inital members of the team who were not former ZGS staff were G. Mavrogrnes from CHM Division, and G. Shenoy, G. Knapp and J. Viccaro from MSD Division. It should be noted that the team enjoyed very strong support from Associate

Laboratory Director for Physical Research, K. Kliewer and from the HEP Division Director, T. Fields.

Although the team spent only a half of the budget in the first year, the second year (FY 85) budget was $1M, and by the end of the second year the team had produced a Conceptual Design Report together with its supporting documentation including the cost and schedule estimates.

Hard work by this handful of people paid off handsomely. In 1986, DOE decided to build what was then called then 6 GeV synchrotron source at ANL. An Associate Laboratory Director-ship for the APS was created in 1987, and the APS Division branched out from HEP Division in 1988. The APS Division further branched to Accelerator Systems Division and an Experimental Facilities Division in 1991.

It is interesting to note that PHY Division gave birth to PAD and the ZGS, and one of the ZGS Division, (HEP Division) gave birth to APS Divisions.

III. MACHINES

The ZGS was a unique machine. Despite the normal wisdom that all separated function machines are of the strong focusing type, it was the first separate of function machines ever built and at the same time it was a weak focusing machine. It was the first machine to accelerate polarized protons to GeV range, and the first US machine to employ the H^- ion injection scheme in a routine way to enhance the transverse phase space. While doing all this frontier development, the ZGS organization raised and trained a large number of highly motivated and skilled scientists and engineers during its tenure of some 15 years. Following are some highlight of accelerator work performed by the former ZGS personnel after the closing.

III.1 IPNS Rapidly Cycling Synchrotron (RCS)

Some years before the closing of the ZGS, as a ZGS intensity improvement program, a 30 Hz RCS was built as a Booster to raise the ZGS injection energy from 50 MeV to 500 MeV. This machine had no opportunity to be used as the ZGS Booster because of closing of the ZGS before its completion. However, this 500 MeV fast cycling synchrotron has become the work horse of generating slow neutrons for condensed matter research both in neutron scattering to investigate the bulk material structure and in radiation damage by neutrons. Jack Carpenter's talk in this conference covers the details of how the IPNS program developed.

Figure III.1-1 shows the layout of the IPNS facility. The old 50 MeV linac designed and built as the ZGS injector linac which had a repetition period of 2 seconds now operates with repetition rate of 30 Hz. The 50 MeV beam turns around 180°, and heads for the RCS in Building 399 which is located under the bridge to the Center Building. The former EPB-II building houses the neutron generating target station.

The machine has been operating for 11 years and 9 billion pulses at the space charge limit of 3 10^{12} protons per pulse. It is the most reliable machine ever. Figure III.1-2 shows the IPNS accelerator system availability since 1981, and the figure shows that the recent years' availability varies between 94 and 96 %, a remarkable performance.

III.2 GEM (GeV Electron Microtron)

The GEM project was to design an accelerator complex to produce a cw electron beam of 4 GeV with a time averaged current greater than 100 μA for the medium energy physics program of the U.S. The science at ANL is centered in the Physics Division. This study occurred during 1982-83. As noted earlier, at the termination of Accelerator Research Facilities Division, a group of accelerator people transferred to the Physics Division to work on the design. There was a competition for this project, that came from a newly formed Southeast Universities Research Association (SURA).

The SURA design of the accelerator system consisted of a full energy pulsed linac and a storage ring which stretches the pulse by extracting the beam slowly.

The ANL design utilized a microtron concept by re-circulating the beam 37 times through the accelerating sections. Figure III.2-1 shows a schematic layout of the GEM, which consisted of a 23 MeV injector linac, a 185 MeV booster microtron and a 4 GeV 6-sided microtron (Hexatron). The Hexatron consisted of 6 sector-magnets and 3 linacs. A pair of the sector magnets were designed to separate the trajectory of each turn as shown in the figure.

The other important point of the ANL design was to use the ZGS buildings. The proposal was to house the Hexatron in the ring building, a monochromatic photon facility in the Meson Building, a high resolution spectrometer in the 30 inch bubble chamber building, and a medium resolution spectrometer facility in the EPB-I building. The proposed arrangement is shown in Figure III.2-2.

We lost the competition to SURA. A DOE review committee favored the pulse-stretcher ring concept over the microtron concept. However SURA abandoned the pulse stretcher ring concept, and they are in commissioning process of a 4-turn re-circulating accelerator. They also named their facility Continuous Electron Beam Accelerator Facility (CEBAF).

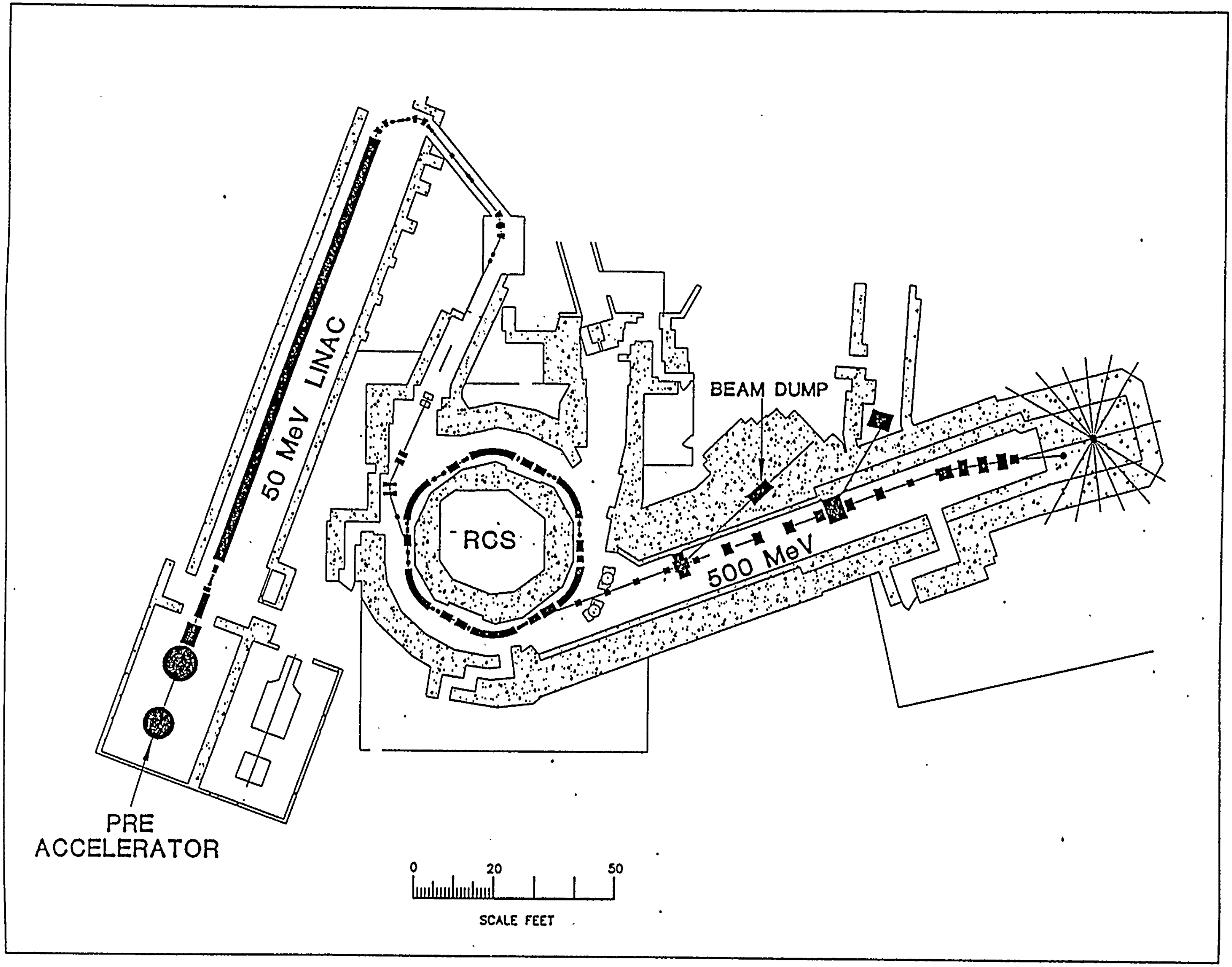

Figure III.1-1
IPNS Facility Layout

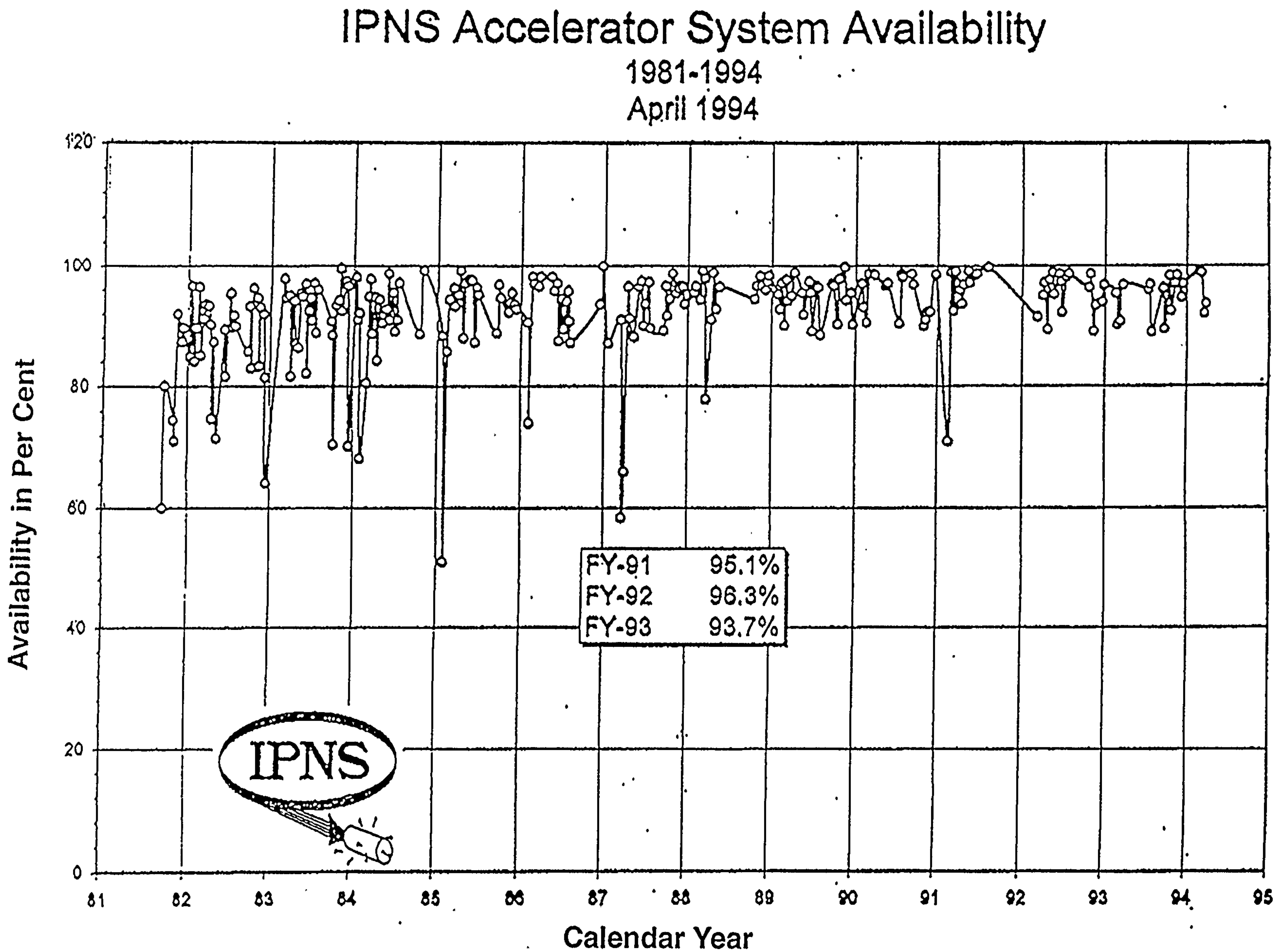

Figure III.1-2
IPNS Facility Availability

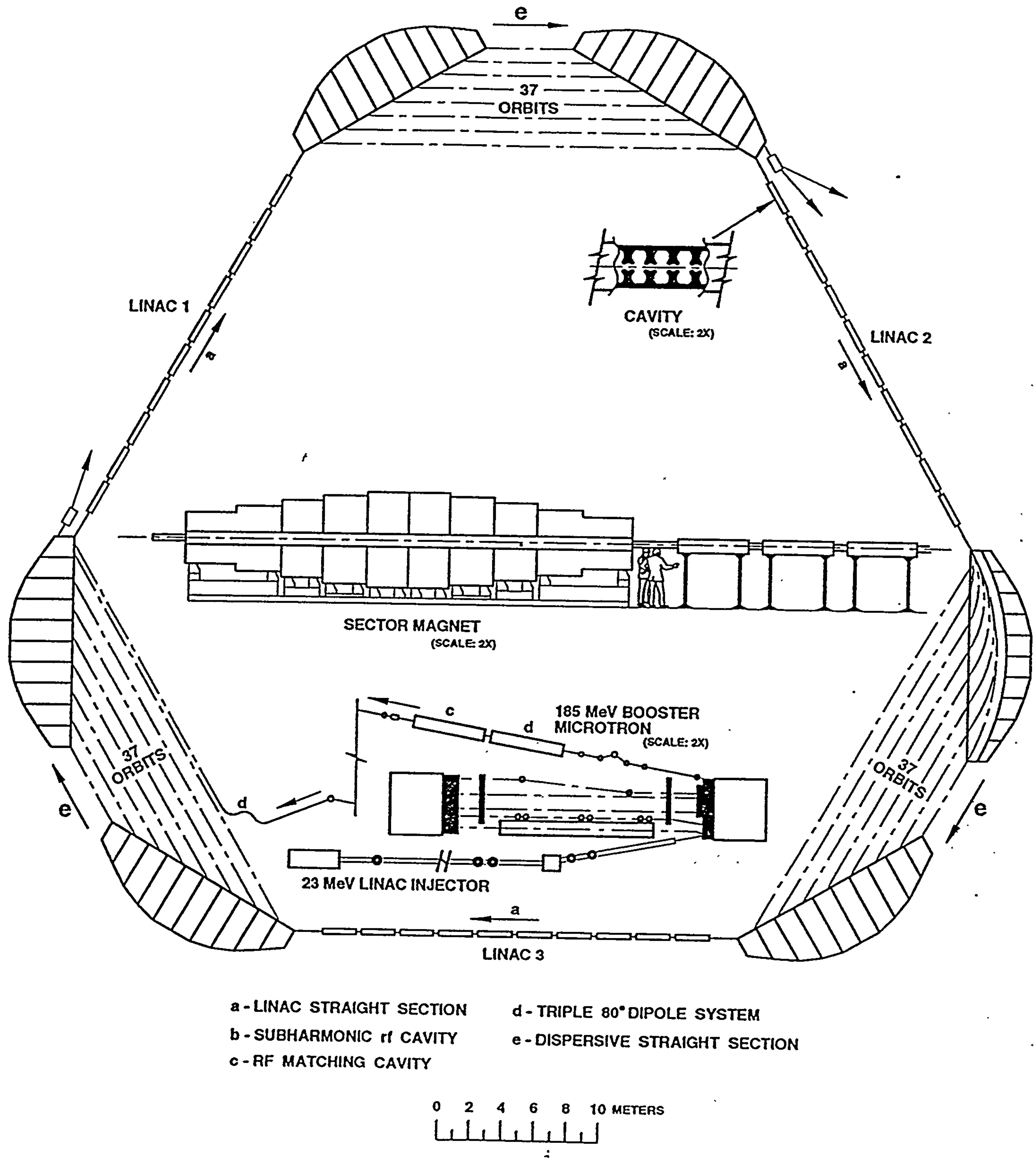

Figure III.2-1
Schematic Layout of GEM Hexatron

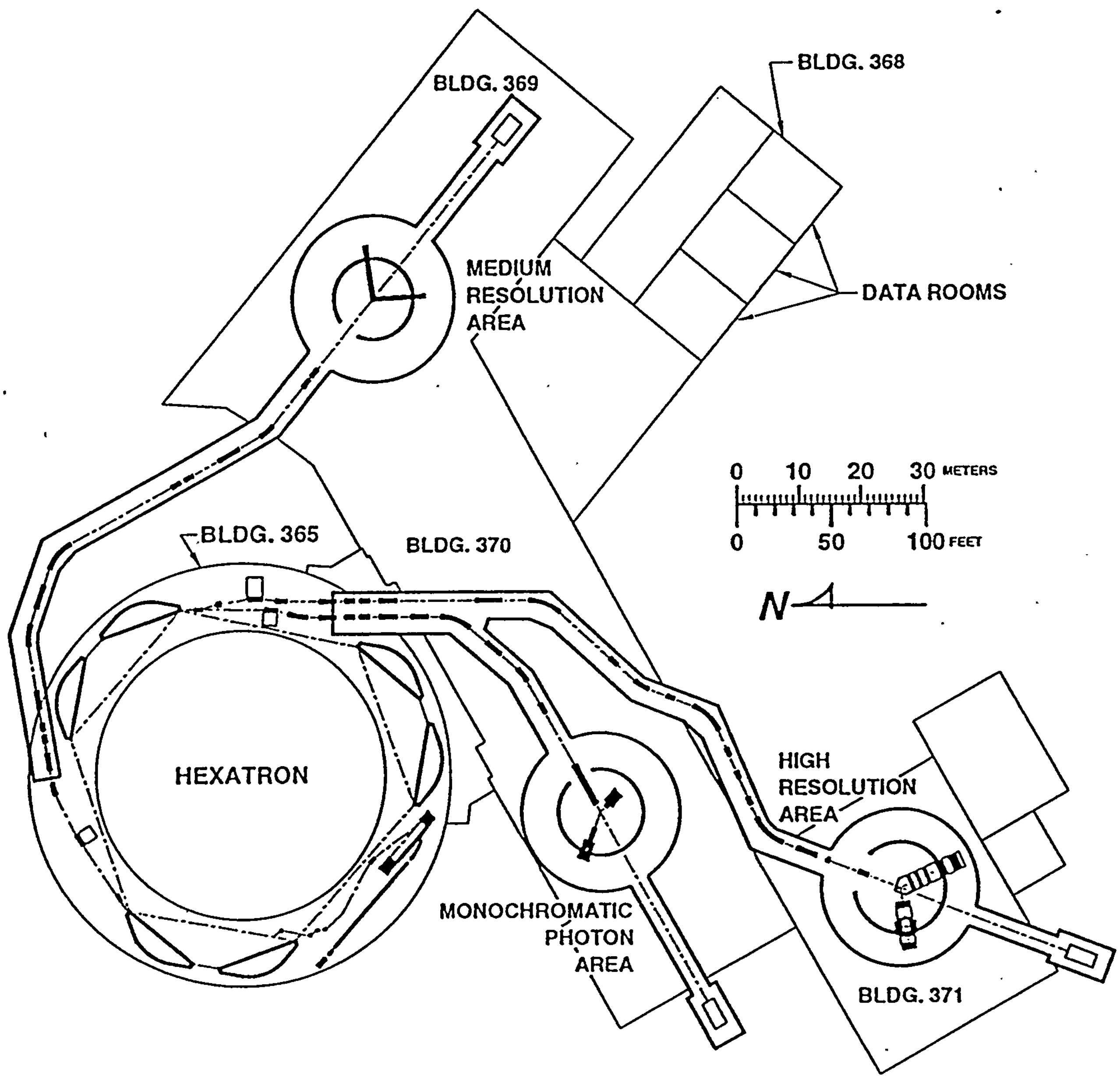

Figure III.2-2
Hexatron and Experimental Facilities
Layout Utilizing the ZGS Builsings

III.3 Argonne Wake Field Accelerator (AWA)

Some of us are constructing and operating high energy accelerators for other scientific disciplines such as x-ray and neutron scattering, and some of us are trying to improve accelerator technology itself. For example, when the SLAC linac was built, the accelerating gradient was 8 MV/m for an electron linac. The present day electron linac has a typical gradient of 20 MV/m. For future multi-TeV linear colliders, higher energy gradients are essential. The AWA, under the leadership of Jim Simpson, is such a development of physics and technology, and is supported by the advanced technology section of DOE's Division of High Energy Physics.

The research addresses the wake field produced by a large charge and very short bunches of electrons. A typical example is 100 nC of electrons in 5 psec (rms.) bunches producing collinear wake fields in slow wave devices and plasmas.

The goals include development of high gradient in excess of 200 MV/m, and demonstration of acceleration of beam energy > 1 GeV in a less than 10 m long structure. The initial test will start in the coming summer.

III.4 Advanced Photon Source (APS)

III.4.1 Birth of APS

The official DOE name for the APS is 6-7 GeV Synchrotron Radiation Source, and following is a brief chronology of how it started.

In November 1983, a DOE committee (Eisenberger/Knotek) advocated construction of a 6-GeV synchrotron radiation source be number one priority for the US synchrotron radiation user community. With this background, I obtained Laboratory management support to start a group to design a 6-GeV synchrotron radiation facility.

In April 1984, a National Academy of Science panel (Seitz and Eastman) reviewed research facilities needs for material research and made priority recommendation to the Office of Science and Technology Policy. The first priority of the recommendation was that the nation should build a 6-GeV synchrotron radiation source. Such a source had been proposed by four institutions: ANL, BNL, Cornell University and Stanford University. The second priority was to build the Advanced Light Source (ALS) a (1-2 GeV Light Source) at Lawrence Berkeley Laboratory, the third as to build the Advanced Neutron Source (ANS) reactor proposed by Oak Ridge National Laboratory, and the fourth was a pulsed neutron source using an FFAG concept proposed by ANL.

During this period, we assembled the former ZGS people who had moved to other programs into the HEP Division to design and write a proposal. The initial budget was

$174K in fiscal year 1984, and $1M for FY 85 which came from Laboratory Director's program development funds.

In early October 1984, there was a meeting at Ames Laboratory, Ames, Iowa of accelerator builders and users to set the parameters of the 6-GeV synchrotron source. The parameters were an energy of 6 GeV, and a stored current of 100 mA as well as other details. The parameters are shown in Table II.4.2-1. Note that the parameter table includes a statement that positrons are to be used rather than electrons. This has to do with the fact that a stored electron beam attracts ions from residual gas ionized by the circulating beam which result degradation of the beam. The way to avoid such ion-trapping is to use positrons. Table II.4.2-1 also shows that the APS parameters which can be compared with the Ames parameters.

By August 1985, a complete concept of the facility was put together so that a bottoms-up cost estimate of the construction project could be commenced.

Table II.4.2-1

Ames and APS Parameters

Parameters	Ames (1984)	APS(1987)
Beam Energy	6 GeV	7 GeV
Beam Current	> 100 mA	300 mA
Beam Lifetime	> 10 h	> 10 h
Number of Bunches	1 - 40	1 - 60
Bunch Duration	10 - 100 ps	10 - 100 ps
Horizontal Emittance	$< 7\ 10^{-9}$ m.rad	$< 7\ 10^{-9}$ m.rad
Circumference	~ 800 m	1060 m
Number of Straight Sections	32	40
Straight Section Length (Standard)	6 m	6 m
Straight Section Vertical Aperture	8 mm	8 mm
Radiation Sources	Undulators, Wigglers, Bending Magnets	Undulators, Wigglers, Bending Magnets
Fundamental Undulator Energy (10 mm ID gap)	20 keV	20 keV (tunable)
Beam Particle	Positron	Positron
Injection Energy	Full Energy	Full Energy

A DOE Review Committee on Technical, Costs, Schedule and Management reviewed the design and construction planning of the facility in May 1986, and recommended to Laboratory management to initiate funding approval.

Soon after the review, the Director of Energy Research (DOE) made a general agreement between laboratory directors to spread large users facilities to several laboratories. The agreement was: 1 - 2 GeV Light Source to LBL, 6-GeV Synchrotron Radiation Source to ANL, RHIC (Relativistic Heavy Ion Collider) to BNL, and ANS (Advanced Neutron Source), which is a reactor based neutron source to ORNL.

What was called in 1986 the 6-GeV Synchrotron Radiation Source became the Advanced Photon Source (APS) in 1987, and the accelerator energy was changed from 6-GeV to 7-GeV in order to provide additional flexibility.

III.4.2 Scientific Capability of APS

A figure of merit of a facility can be measured either with beam energy or beam intensity. Since Roentgen discovered x-rays in 1895, beams of x-rays have been used for all kind of scientific and technological endeavors. Figure III.4.2-1 shows the historical development of the brilliance of x-rays since the advent of x-ray tube by Roentgen. The figure shows that during the first 60 years of x-ray history, brilliance of x-ray sources were around $10^7 \sim 10^8$ photons/sec $mm^2 mr^2$(0.1%band width) coming from x-ray tubes. Utilization of electron synchrotrons in 1970s changed the brilliance to 10^{12} range, and this era is called the first generation synchrotron source. In this period synchrotron facilities belonged to the high energy physics program, and x-ray users used the facilities in a parasitic mode to the high energy experimental program. In late 70s, several dedicated facilities were built throughout the world, and these we call the second generation sources. These sources have brilliance of order of $10^{14} \sim 10^{15}$, and energies of the accelerators less than 3 GeV. The APS, a third generation source is produce brilliance of order of 10^{19} as shown in the figure.

In a technical jargon, "the APS facility is optimized to produce insertion device (ID) hard x-rays with brilliance better than 10^{19}." Then a question is what kind of science one can do with four orders of magnitude brighter x-ray source. Simple extrapolation indicates that the new x-ray source will open new research capabilities. For example, the increase in brightness means one can use smaller samples to get a similar results as today's facility and/or one can reduce exposure time of the sample. This ability to use smaller samples and/or shorter exposure time opens up new areas of research. Analyses of the structure of proteins, virus, living cells, geological micro-crystals, x-ray motion pictures, and so on.

Figure III.4.2-2 shows the brilliance of various sources as a function of photon energy. This figure shows that the APS covers a wide range of x-ray energy from a few keV to 100 keV range with unprecedented brightness. Figure III.4.2-3 shows a schematic of an undulator constructed with permanent magnets arranged as shown. When positron beam passes through the device, the magnetic fields in the device causes the beam to undergo an undulating wave motion. Every time the beam changes its direction of motion it emits photons, and the photons from one wave make constructive interference with photons from another wave. This results in a discrete energy of photons emerging from the device

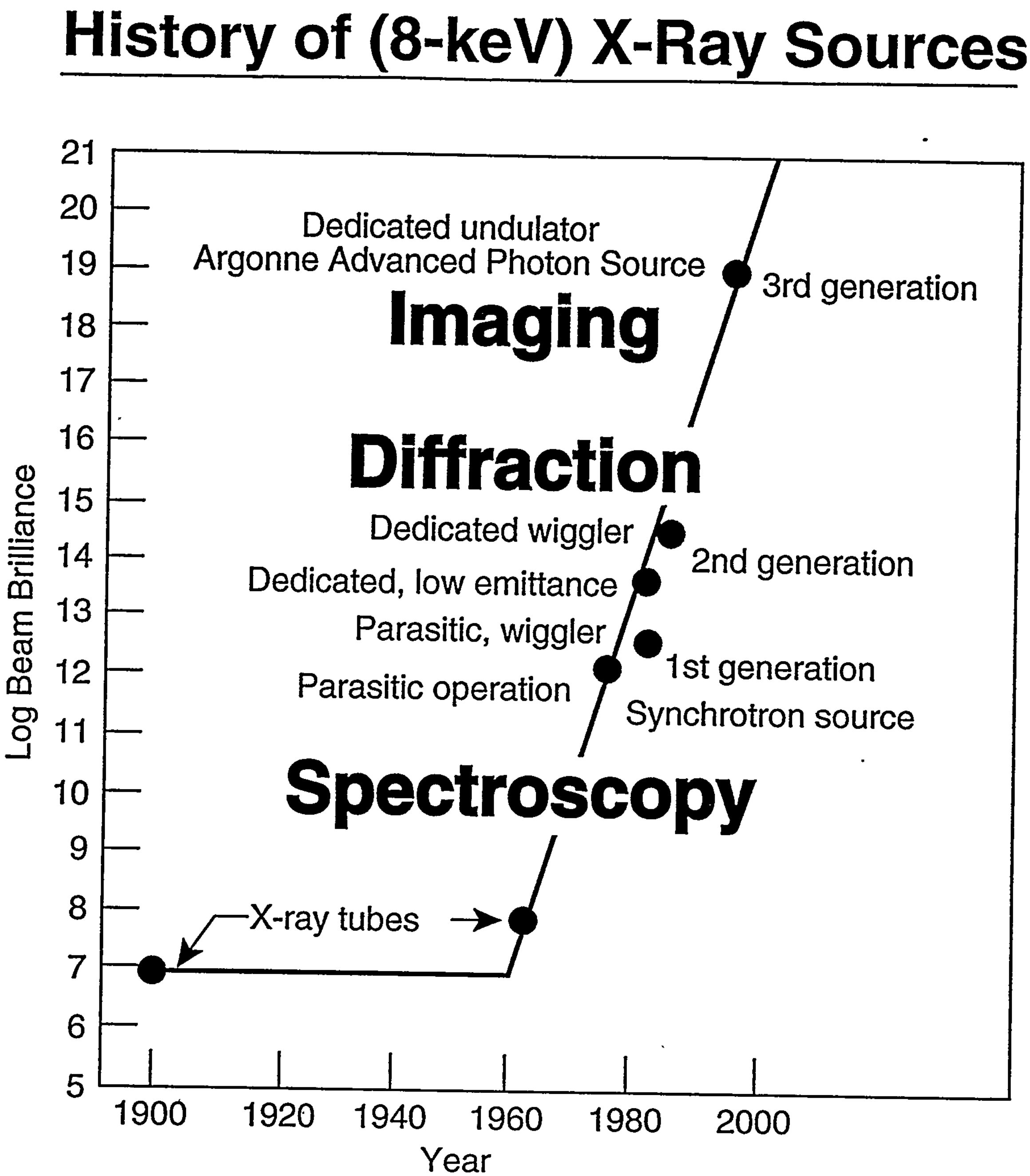

Figure III.4.2-1
History of x-ray Brilliance

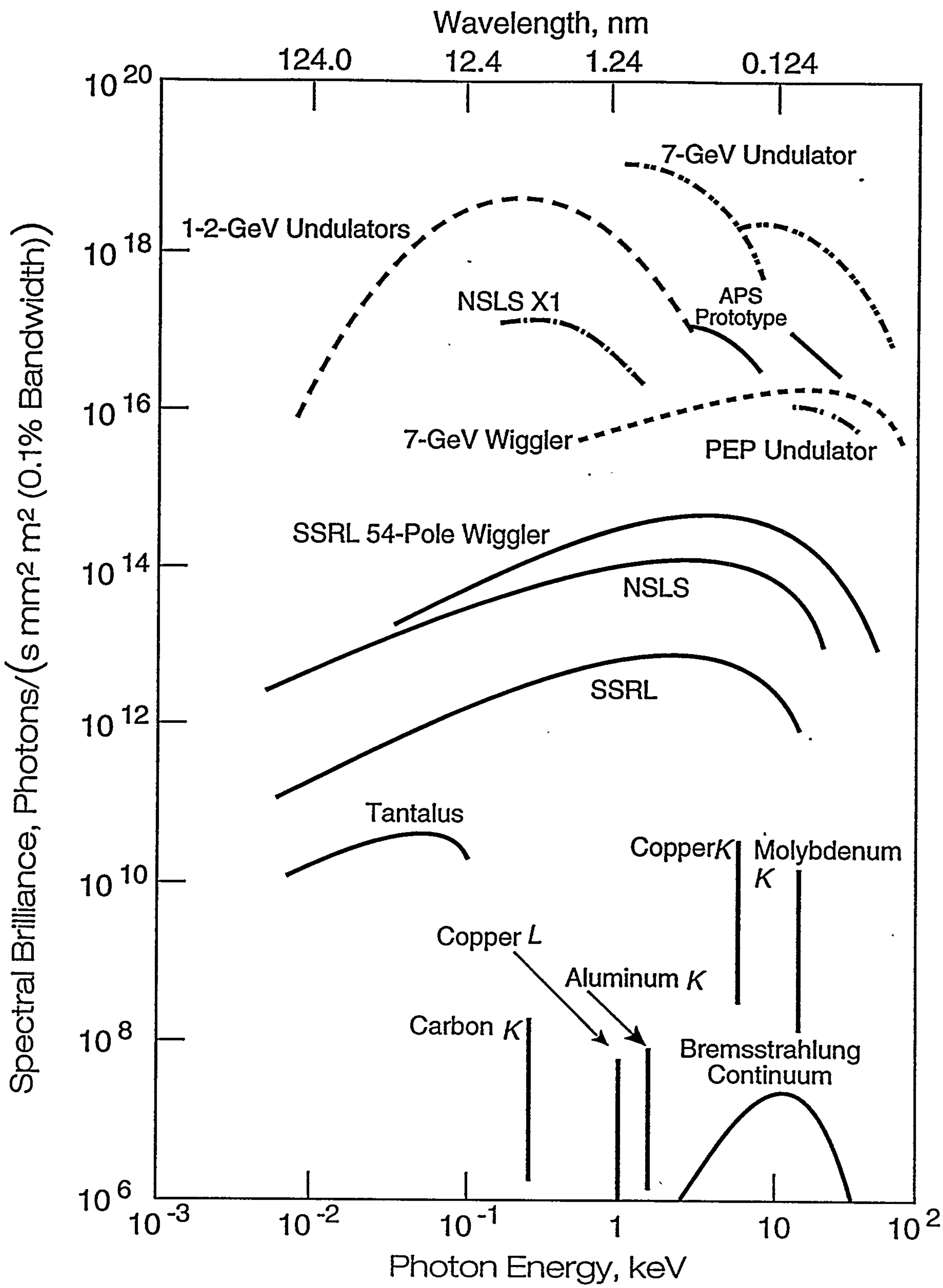

Figure III.4.2-2
Brilliance of Various Sources as a Function of Photon Energy

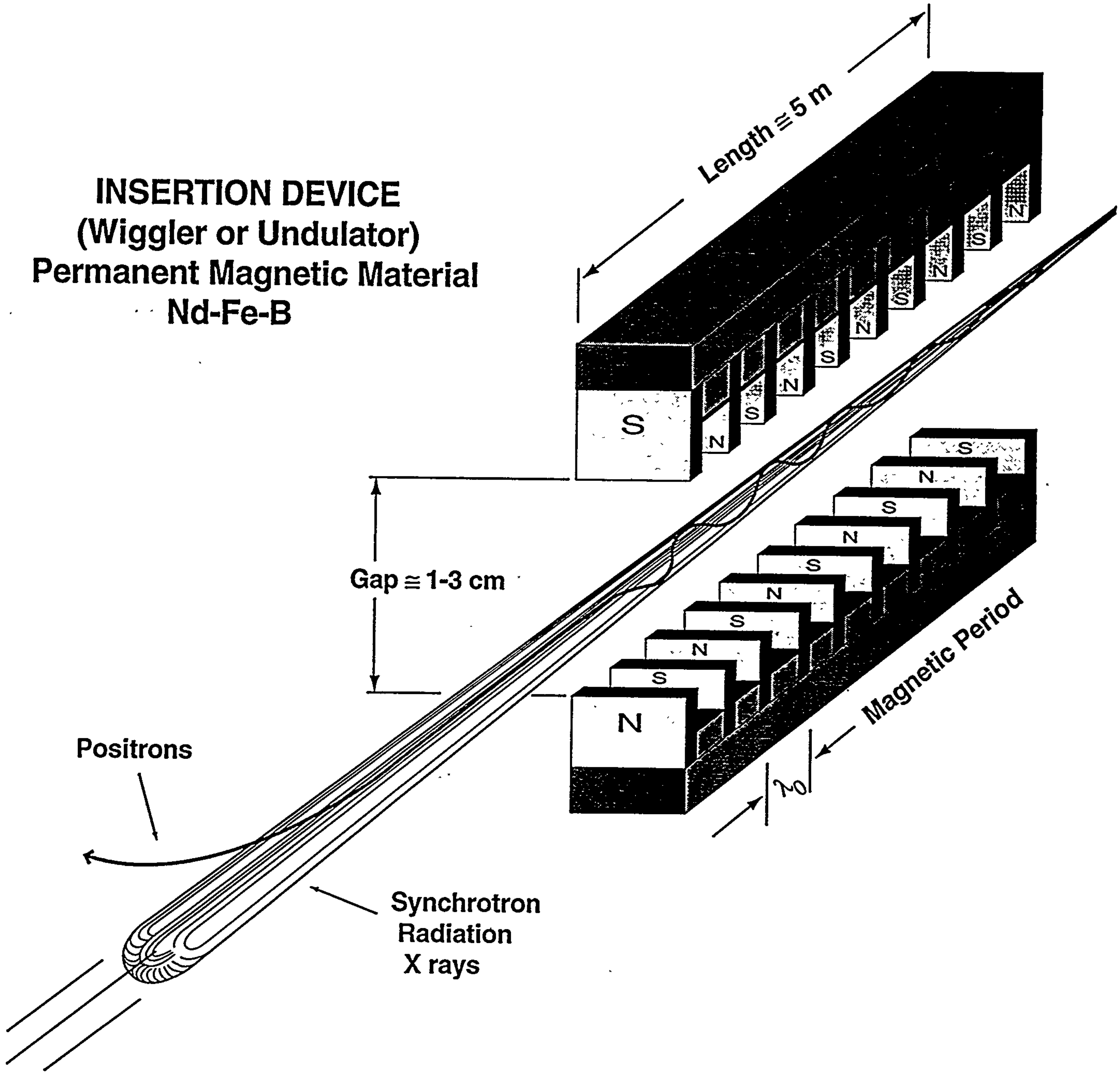

Figure III.4.2-3
Schematic of an Undulator

depending on the magnetic periodicity of the undulator and the field strength of the device. In another word, one can tune the photon energy by adjusting the gap height of the device which changes the magnetic field.

III.4.3 Accelerator Configuration

As noted in the Ames parameters, the accelerator system is to utilize positrons and a full energy injector. The original plan was to locate the APS near the ZGS complex to take advantages of existing utilities and infrastructure. However a detailed study showed that a better location could be the southwest corner of the laboratory boundary as shown in Figure III.4.3-1. This corner is called 400 Area in contrast to the 300 Area of the ZGS.

A detailed layout of 400 Area is shown in Figure III.4.3-2. A linac system consisting of an electron and a positron linac is house in Building 411. These are a 200 MeV electron linac capable of delivering 50 nC charges in 30 nsec pulse with a repetition rate of 60 Hz to a positron production target, followed by a 450 MeV positron linac.

The Positron Accumulator Ring (PAR) which accepts 24 positron linac pulses with 60 Hz rate, and lets the accumulated beam damp for 100 msec before ejecting the damped beam for injection to the booster synchrotron for every 1/2 sec. The PAR has a circumference of 30 m, and is housed in Building 412, which is called Injection Building.

The Booster synchrotron accelerates the 450 MeV positrons to 7 GeV with a repetition rate of 2 Hz.

The center piece of the facility is the storage ring. The ring and some 70 beamlines together with experimental setups are housed in Building 400 as shown Figure III.4.3-2. The circumference of the ring which consists of 40 sectors, grew to 1104 m during the detailed design process from the 1060 m noted in Table III.4.2-1. Each sector has 2 dipole, 10 quadrupole, and 7 sextupole magnets. Figure III.4.3-3 shows the magnetic lattice of one sector. Photon beam paths from ID and dipole magnet are also shown in the figure.

In order to facilitate passage of the photon beams emerging tangentially from the ring, we had to invent a suitable vacuum chamber geometry. The geometry of the chamber is called Bob Wehrle and John Moenich's FISH which is shown in Figure III.4.3-4. This geometry allows not only the photons to pass through without interception but also facilitates a continuous pumping along the circumference of the ring. The chamber system consists of a beam chamber and an and the ante-chamber where a distributed getter system is installed. Figure III.4.3-4 shows both the beam chamber and the ante-chamber. The photon beam passes through the narrow channel between two chambers.

The magnetic lattice of the storage ring also has to accommodate the passage of the extracted photon beam. To do this, Walter Praeg and Ken Thompson invented a

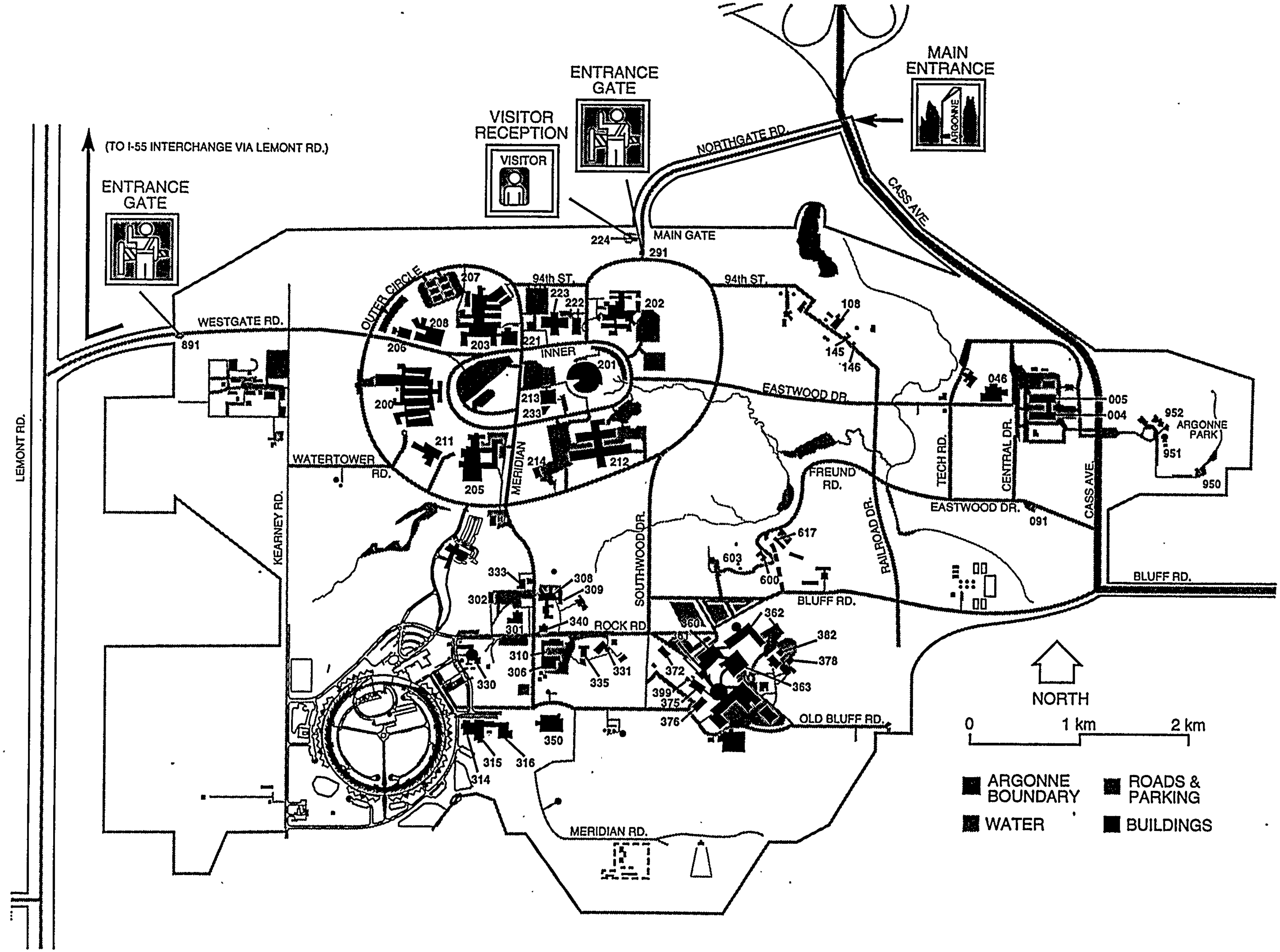

Figure III.4.3-1 ANL Site Drawing Showing the APS Site

Plan View of the Advanced Photon Source

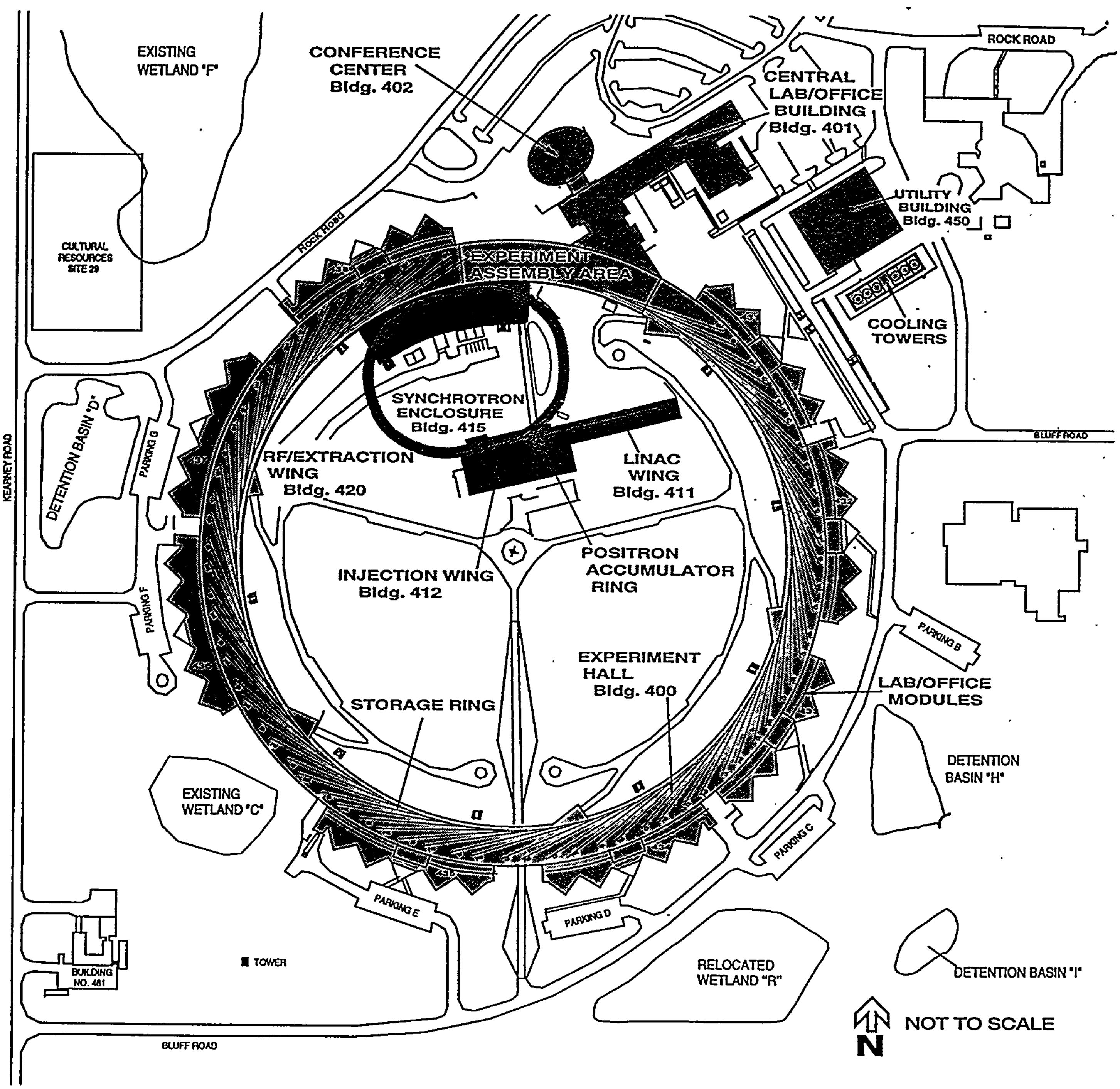

Figure III.4.3-2
Layout of 400 Area Showing the APS Buildings

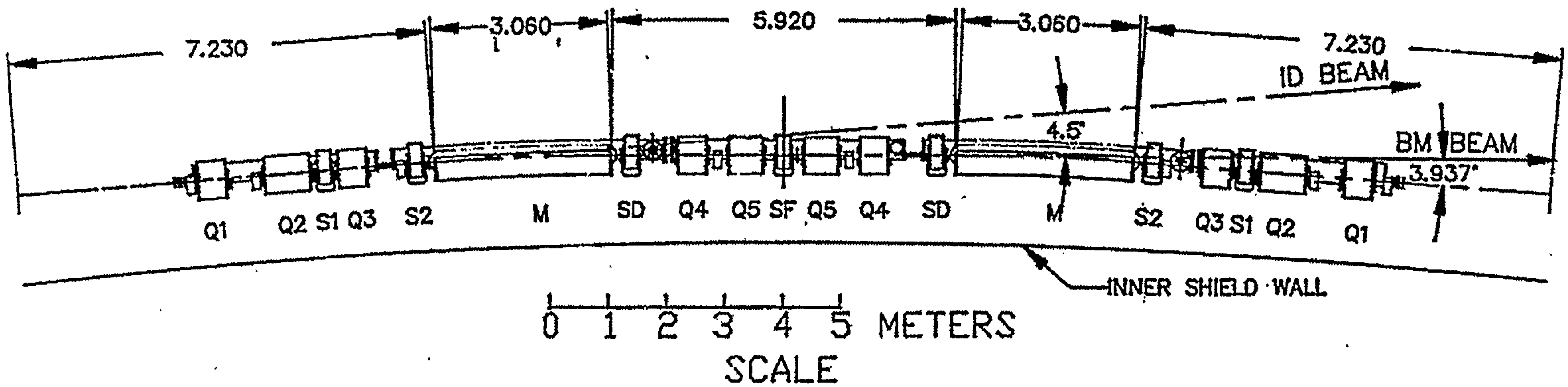

Figure III.4.3-3
Magnetic Lattice of a Sector

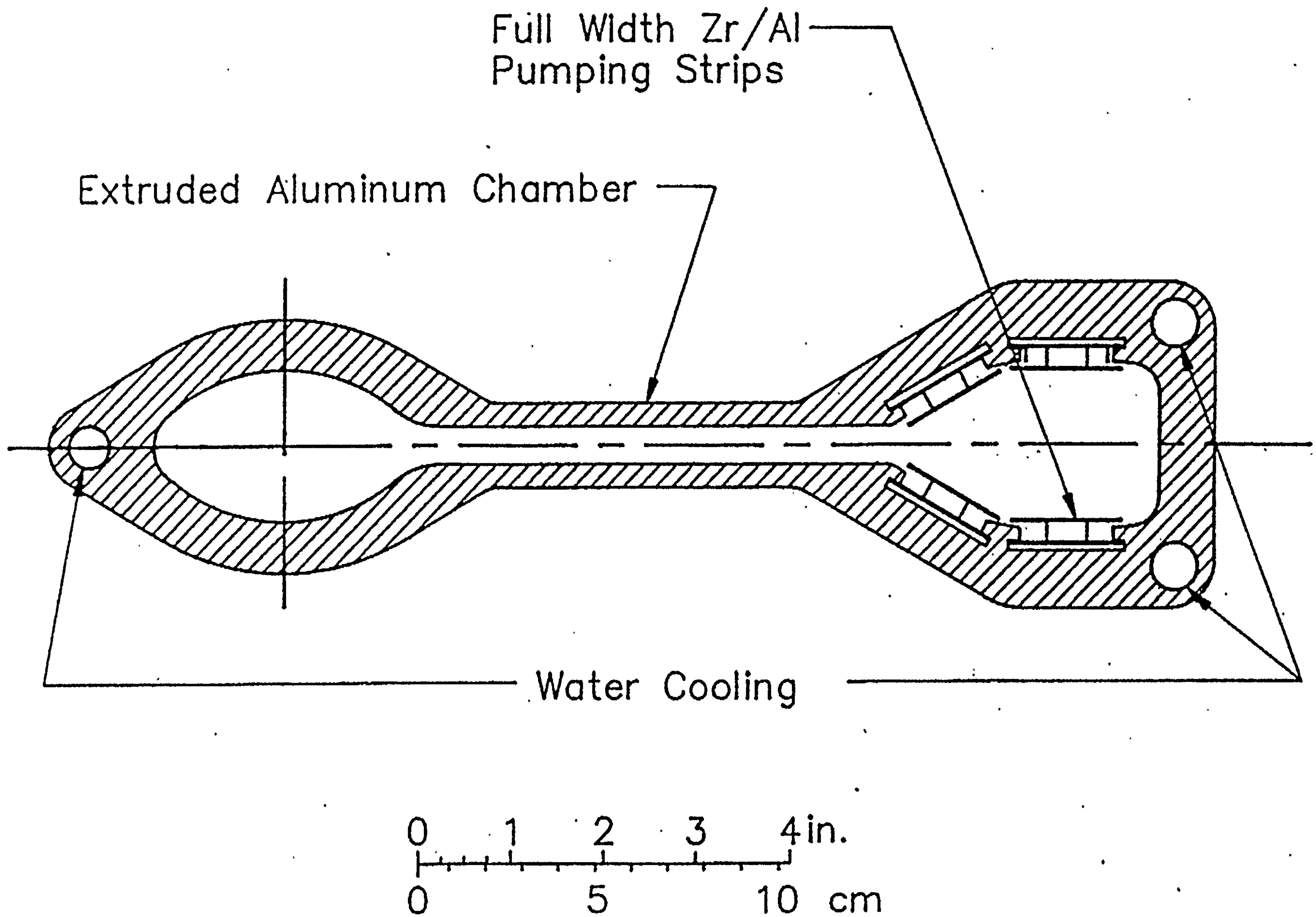

Figure III.4.3-4
Storage Ring Vacuum Chamber Cross Section
"FISH"

"FIGURE 8" quadrupole magnet, where two of four of the magnetic field return yokes were removed so that the magnetic field lines make a figure 8. This is shown in Figure III.4.3-5. This figure also shows how the fish-shaped vacuum chamber system fits into the magnet.

The accelerator system uses 6 of the 40 long-straight sections in the ring. The remaining 36 straight sections from 36 sectors are to be equipped for the users scientific program. The plan is that each sector will have one ID beam line and one dipole magnet beam line. Therefore there will be total of 68 beam lines. A layout of sectors, associated beam lines, and users office and laboratory modules are shown in Figure III.4.3-6. As shown in the figure, each sector will have 2 laboratory spaces, 8 offices and a conference room.

For the management of the scientific program, we use the CAT (Collaborating Access Team) concept. A consortium of users proposes a program of experiments to be performed. Once their scientific program is approved, the team obtains the funds for the beamlines and equipment. The CAT uses 75% of the beam time, and 25% goes for independent users.

So far we have approved programs for 20 sectors. The initial funds needed for the 20 sectors are some $180M, and they have obtained some $100M so far.

It is very interesting to note that we have heavy involvement by industry; AT&T, Dow Chemical, Du Pont, IBM, AMOCO and some 15 pharmaceutical companies to name a few.

The total project cost of the APS is $892M, which includes the construction cost of $467M, the pre-construction R&D and other start-up costs. It is anticipated that the annual operating cost to be about $90M with the facility staff of some 350 personnel. Figure III.4.3-7 shows the construction milestone vs. cost.

Figure III.4.3-8 shows a picture of the APS site before the construction started seen from the weather tower. Figure III.4.3-9 shows the APS as of today.

III.5 IPNS Upgrade

As noted in Section III.4.1, the Seitz-Eastman Panel reviewed and recommended that the ANS, a reactor source at Oak Ridge be the third priority, and the 4th be a pulsed source. That was in 1984. Since that time activities of proponents of pulsed neutron sources were dormant until a group of Europeans started to organize a consortium of European Laboratories to advocate a 5 MW pulsed source called ESS (European Spallation Source) in 1991. I had actively participated in the birth of the ESS, and at the same time obtained small funds to form an ANL study group of a pulsed source.

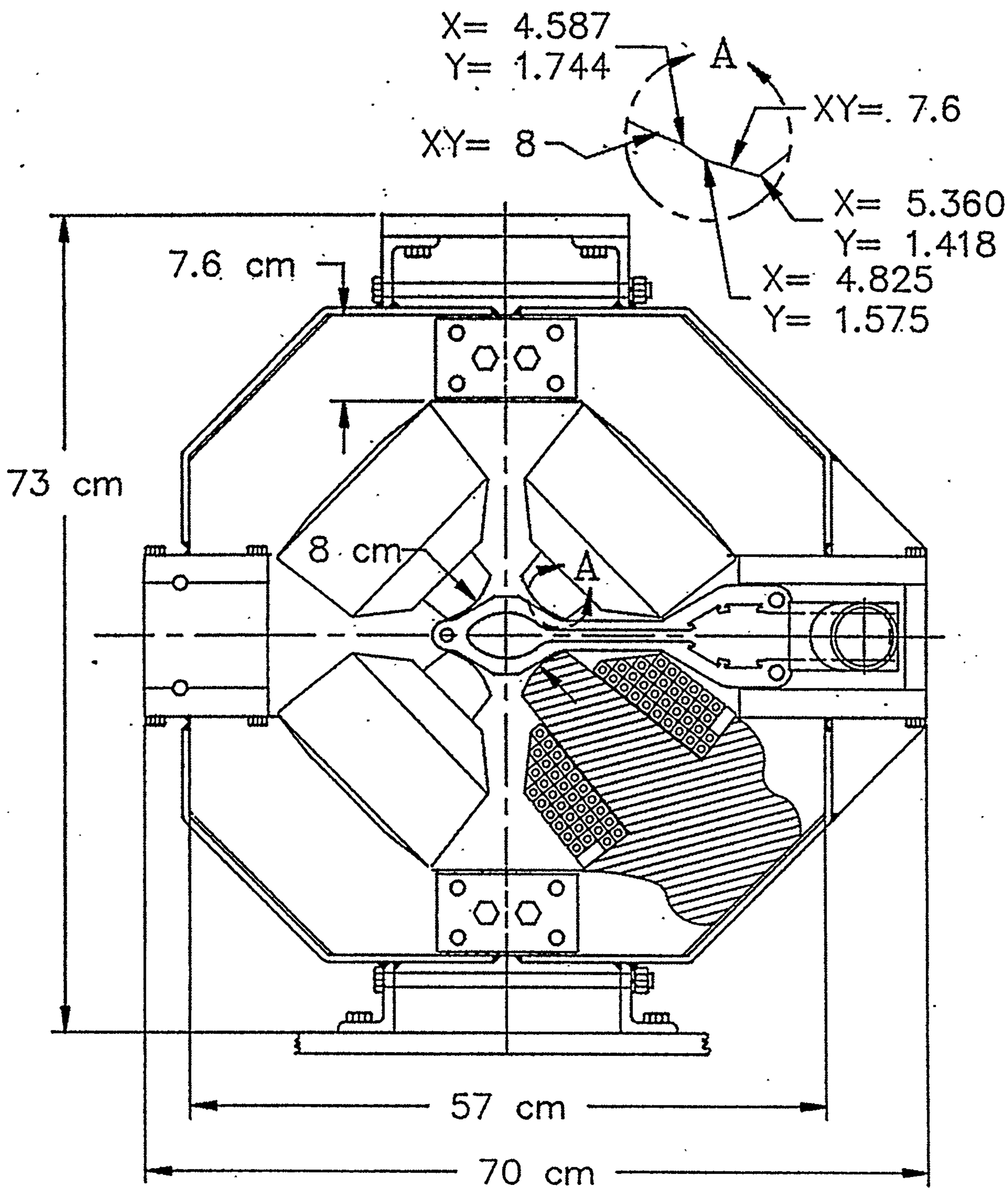

Figure III.4.3-5
"Figure 8" Quadrupole Magnet

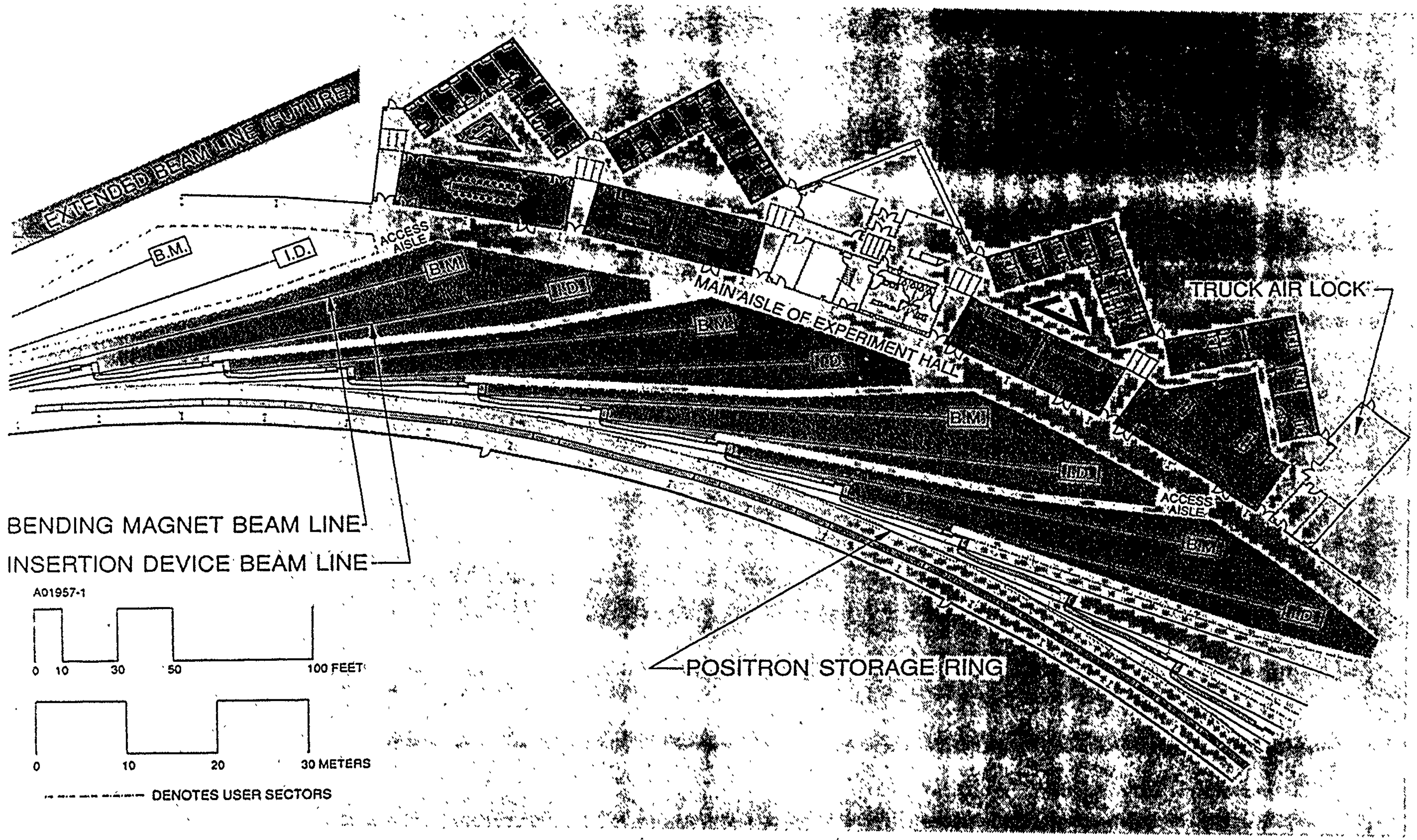

Figure III.4.3-6
Experimental Area Layout Showing
Users Laboratories and Offices Associated with a Sector

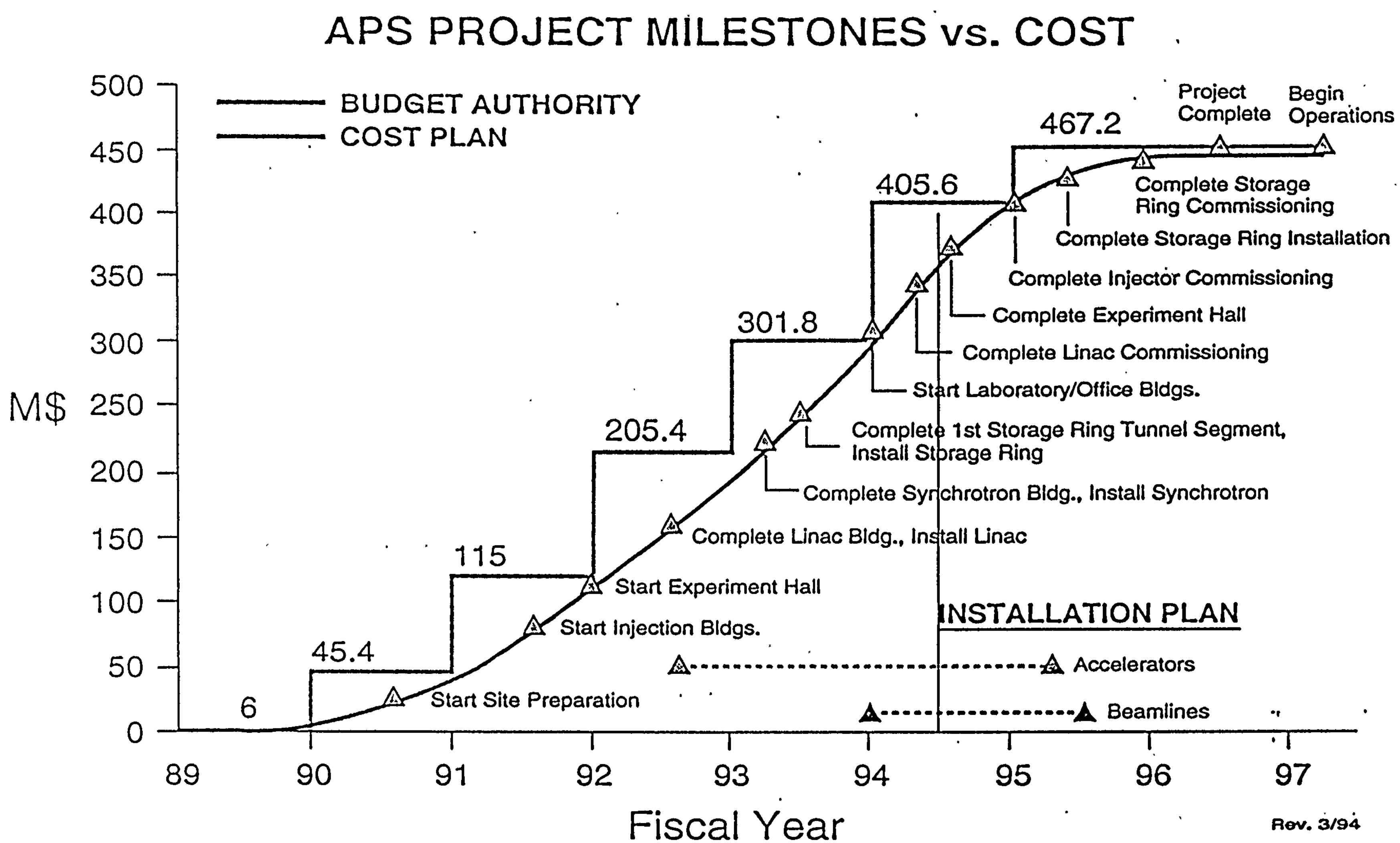

Figure III.4.3-7
Construction Schedule Milestone vs. Cost

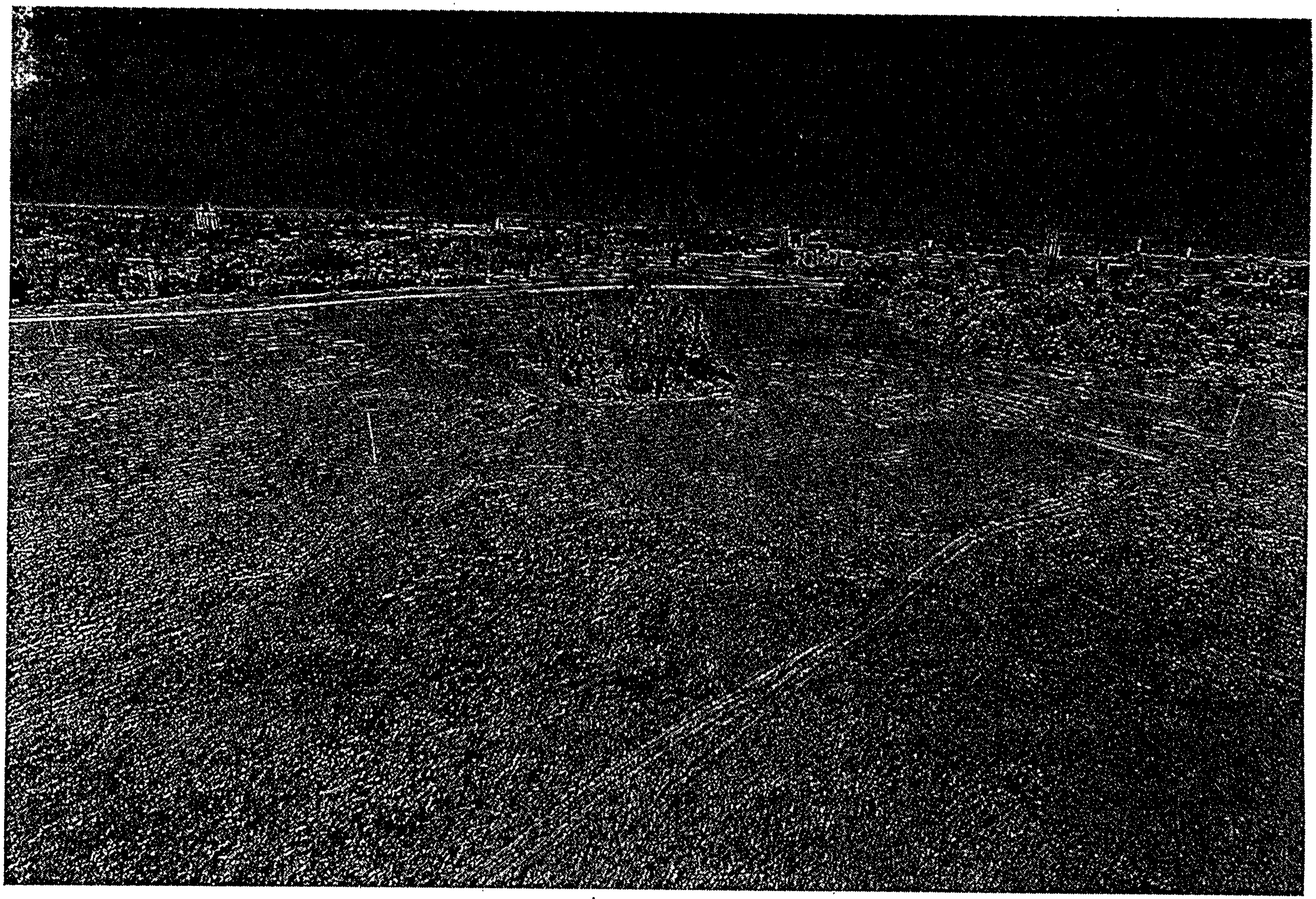

Figure III.4.3-8
APS Site Before Construction

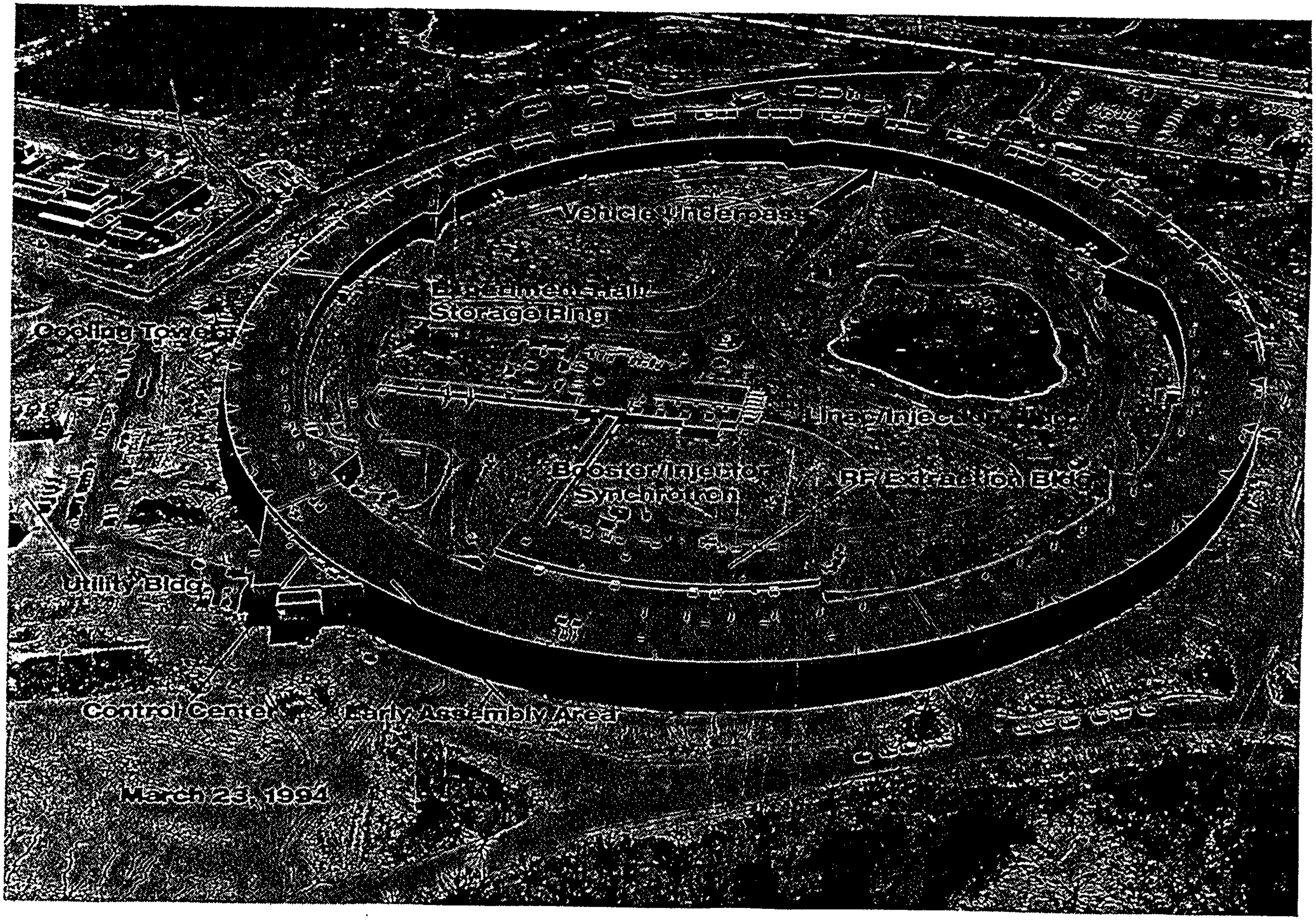

Figure III.4.3-9
APS Site Today Showing Progress of Construction

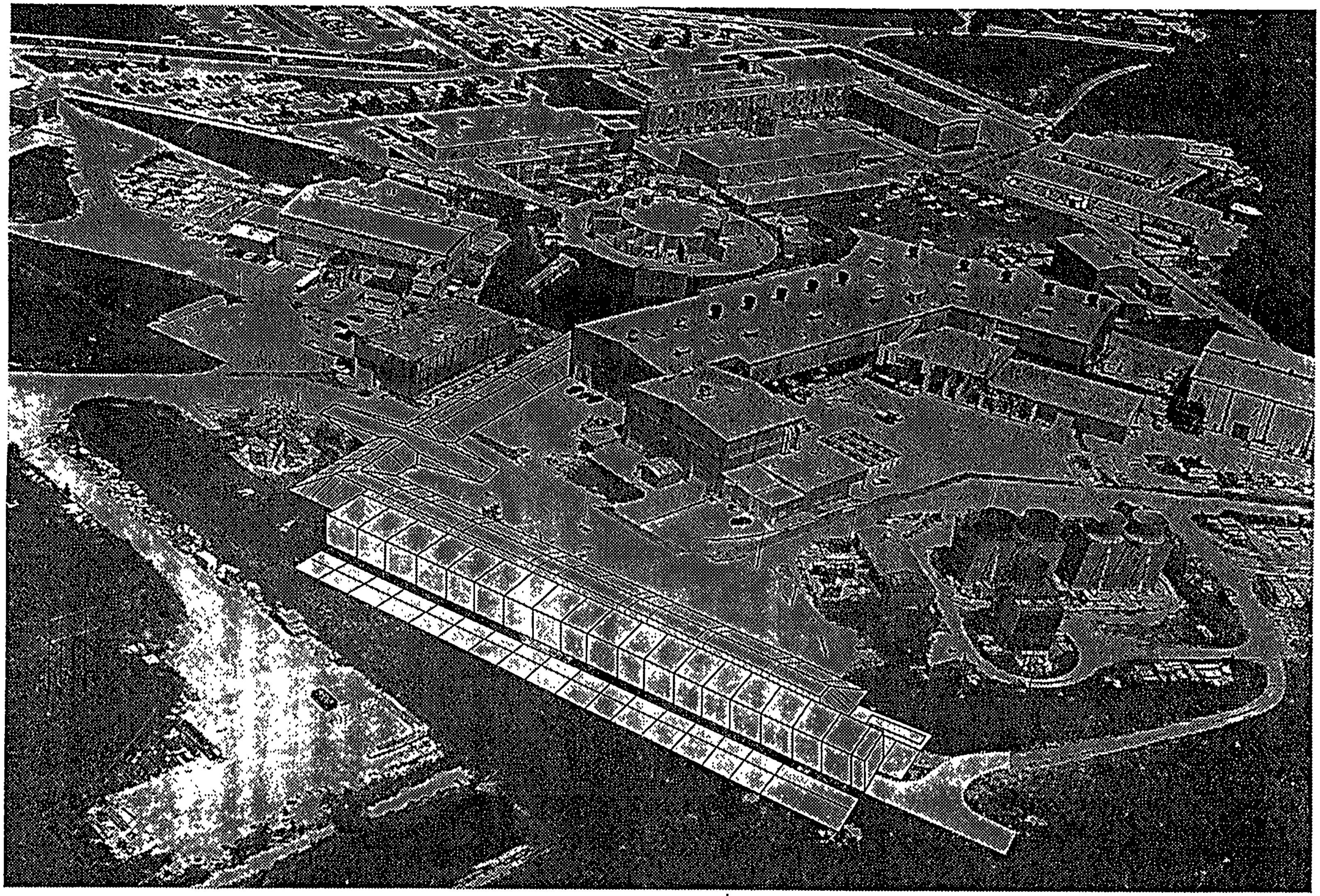

Figure III.5-2
Aerial View Of the ZGS Area with
New Linac Building Sketched in

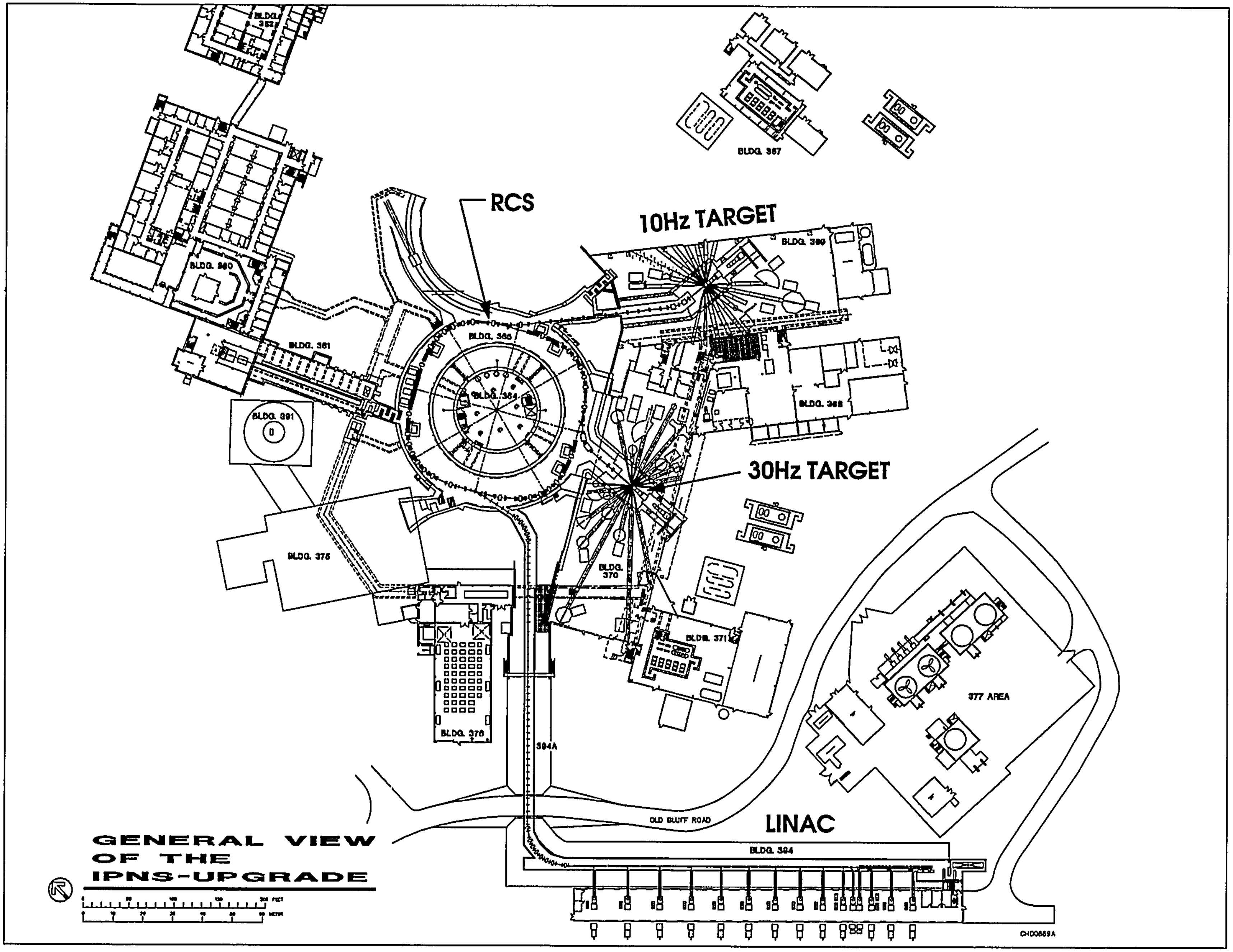

Figure III.5-1
IPNS Upgrade Layout
Using ZGS Buildings

In 1992, DOE Basic Energy Science Advisory Committee (BESAC) appointed a sub-panel (known as the Kohn Panel) to review the situation regarding neutron sources in the US. The Kohn Panel recommended that (1) the ANS, a reactor source in Oak Ridge continue as the number one priority, and (2) the US should pursue a 1 MW pulsed source as a complementary facility to the ANS, and there should be a competitive design effort for the 1 MW pulsed source.

In response to the Kohn Panel recommendation, groups from both ANL and Los Alamos National Lab. (LANL) are pursuing feasibility studies. LANL already has an 800 MeV proton linac which can deliver 1 mA beam current. LANL proposes to build an accumulator ring to compress the linac pulse length to the required 1 microsecond or less.

The ANL plan is to use the existing ZGS building and infrastructure to house and operate 1 MW synchrotron. The book value of the replacement cost of the ZGS complex is about \$150M ~ \$200M, so there is a potential of saving some \$150M.

A 2 GeV rapid cycling synchrotron operating at 30 Hz repetition rate is to be housed in the ZGS tunnel. The synchrotron delivers 10^{14} protons/pulse to make 0.5 mA time averaged current. There will be two neutron generating targets; one receiving the proton beam at 10 Hz rate and the other receiving at 30 Hz rate. The 10 Hz target station is to be place in Building 369 (EPB-I), and the 30 Hz at Building 370 (Meson Building).

There will be a 400 MeV linac system for the injection into the RCS. The linac system consists of a negative hydrogen ion source, a 2 MeV radio-frequency quadrupole, a 70 MeV drift-tube linac, and a coupled cavity linac to make the beam 400 MeV.

Figure III.5-1 shown the layout of the facility. Note that Building 376 (ZGS MG set building) is to house the power supplies associated with the RCS, Building 371 (30 inch Hydrogen Bubble Chamber Building) is to support the 30 Hz target, and Building 367 (40 inch Hydrogen Bubble Chamber Building) is to support the 10 Hz target. Only new building construction needed for the upgrade is a new linac building (Building 394) and the low energy beam transport line.

Figure III.5-2 shows an aerial view of the ZGS Area with new linac buildings sketched in.

IV. SUMMARY

The ZGS as a facility and an organization provided us with an opportunity to learn, to grow, to mature and to contribute in a major way to the basic science facilities of the country. That is the legacy of the ZGS.