OVERVIEW OF THE ADVANCED PHOTON SOURCE (APS)*

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Abstract

The Advanced Photon Source (APS) is a state-of-the-art synchrotron light source facility dedicated to the production of extremely brilliant x-ray beams for research [1]. Its super-intense x-ray beams will be used in many areas of research including industrial research, biological and medical research, defense-related research, and basic research. The APS x-ray beams will allow scientists to study smaller samples, more complex systems, faster reactions and processes, and gather data at a greater level of detail than has been possible to date. Creation of these beams begins with electron production by an electron gun with a thermionic cathode. The electrons are accelerated to 200 MeV by a linear accelerator (linac) and then impinge on a tungsten target, resulting in electron-positron pair production. The positrons are accelerated to 450 MeV in the remainder of the linac, then accumulated, damped, and transferred to a synchrotron that increases their energy to 7 GeV. The 7-GeV positrons are injected into a storage ring, where they pass through special magnets that cause them to emit x-rays of the desired quality. Construction at ANL is nearly complete at this time, and the APS will begin operating for users in 1996. The accelerator and experimental facilities are described in this paper, and a brief overview of some of the experimental programs is given.

I. INTRODUCTION

The Advanced Photon Source (APS) is a national materials-science research facility. When the facility is fully operational, as many as 2000 scientists per year from industry, universities, medical schools, and research laboratories, both federal and private, will conduct frontier experimentation at the APS.

X-ray beams are ideally suited to a broad range of applications. Most of what we know about the three-dimensional nature of atoms in DNA, RNA, and viruses has come from x-ray research. Synchrotron x-ray light sources have also allowed scientists to conduct molecular-level examinations of ceramics and semiconductor materials, both of which are essential to the development of designer materials for new technologies.

High-energy particle accelerators were first constructed in the 1940s to enable physicists to study the fundamental laws of nature. Synchrotron radiation was viewed as a problem, as it limited machine performance. It was experimentally studied in 1946, and was observed at the General Electric Research Laboratory's 70-MeV synchrotron. Scientists at Cornell University in 1956 were the first to use synchrotron radiation in experiments. Synchrotron radiation is the electromagnetic radiation emitted by relativistic charged particles moving in a curved orbit, and the radiated power is given by:

$$P = \frac{2}{3}\frac{e^2 c}{\rho^2}\beta^4\gamma^4 \propto \frac{E^4}{m^4} \qquad [1]$$

where e is the electric charge, c is the speed of light, m is the particle's mass, ρ is the orbit radius, and β and γ are the standard relativistic parameters. A typical electron or positron accelerator emits synchrotron radiation in a broad range of photon energies from microwaves to hard x-rays and gamma rays. The use of accelerators as synchrotron light sources has evolved quickly, since accelerators provide electromagnetic radiation in spectral regions for which no other sources of comparable brightness exist, e.g., most of the ultraviolet/soft x-ray range and hard x-rays. As seen from Equation [1], radiated power increases with decreasing mass, thus electrons and positrons that have small masses are used as the radiators in synchrotron light sources. The narrow cone of radiation is directional with an opening angle of $1/\gamma$, and is shown in Figure 1.

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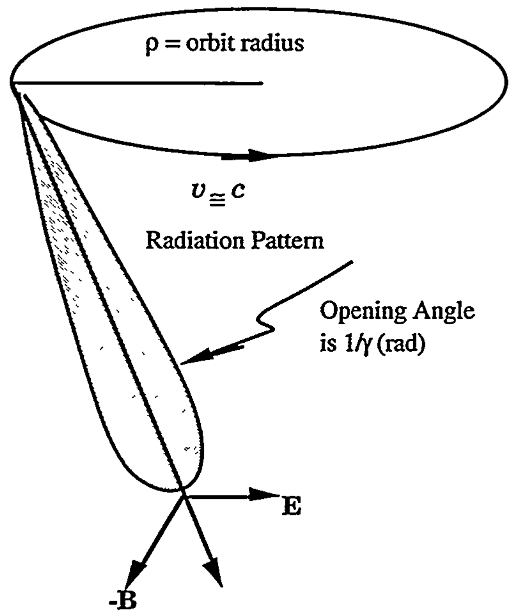

Figure 1: Synchrotron Radiation Pattern.

Radiative energy loss per turn, ΔE, is given by:

$$\Delta E = \frac{4\pi}{3}\frac{e^2}{\rho^2}\beta^3\gamma^4 ,$$

that reduces in practical terms for electrons or positrons to:

$$\Delta E(keV) \approx 88.5\frac{E(GeV)^4}{\rho(meters)} .$$

This is the minimum amount of energy that must be resupplied to the circulating particles by the accelerator's rf system or the beam is quickly lost.

Sources of synchrotron radiation for scientific inquiry have become essential to industrialized nations; more than 30 are either under construction or in operation worldwide. These facilities offer scientists access to an extensive variety of research techniques that can be used in almost any discipline.

II. THE APS ACCELERATORS

The injector and source of particles for the APS accelerator system is a 2856-MHz S-band, electron-positron linear accelerator [2], shown in Figure 2. Positrons are used in the APS storage ring in order to avoid ion trapping. Electrons are emitted from the surface of a thermionic cathode in an electron gun. The APS electron linac accelerates 30-nsec-long pulses containing 50 nC of electrons to an energy of at least 200 MeV. Dipole magnets are used to steer the beam, and focusing is performed using solenoid and quadrupole magnets. Radiofrequency power is provided by 35-MW pulsed klystron amplifiers powered by 100-MW pulsed modulators, and SLED cavities. Power from the klystrons is transported via vacuum transmission waveguide to 3-m-long disk-and-washer accelerating structures. The 200-MeV electron beam is then focused to a 3-mm diameter spot on a 7-mm-thick water-cooled tungsten target that serves as a positron converter. Pair-produced positrons and electrons are refocused by a 1.5-T pulsed coil, and are directed into the positron linac where they are captured and accelerated to 450 MeV ±1%. The design positron current of 8 mA has been achieved.

The positrons are transported to a 30.7-m circumference circular accelerator, the positron accumulator ring or PAR, shown in Figure 3. The PAR accumulates 24 linac pulses each half-second, capturing them

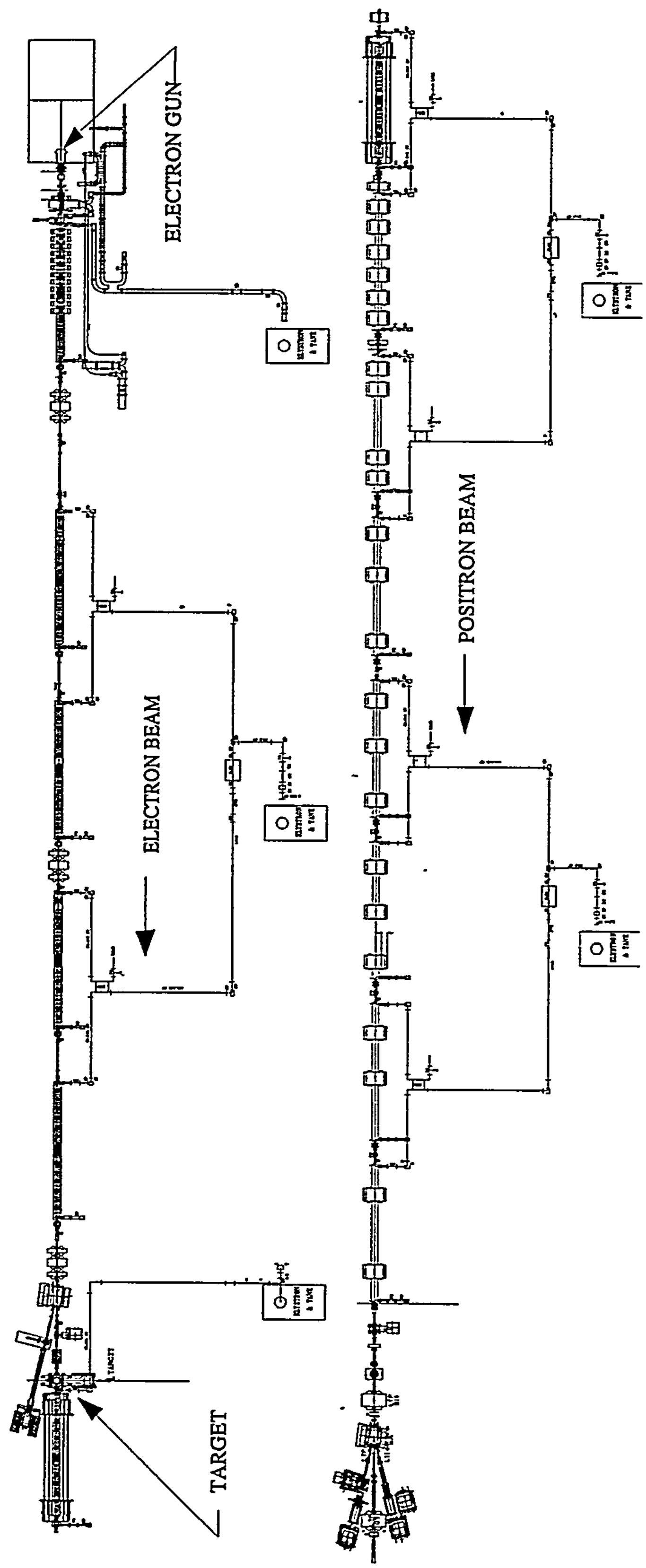

Figure 2: A schematic view of the linac. The electron and positron linacs are separated for ease of viewing; the scales are different for the two parts.

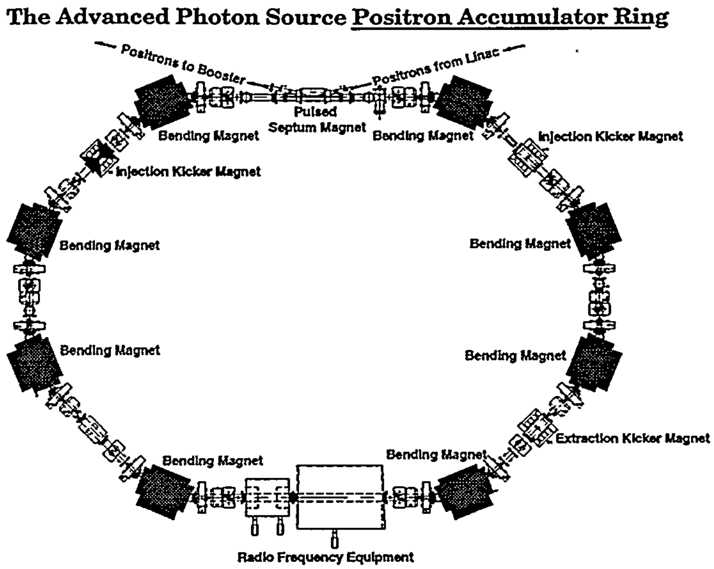

Figure 3: Schematic diagram of the PAR.

with its 9.77-MHz fundamental-frequency rf system, and then longitudinally compressing them with a 12th-harmonic rf system. The 450-MeV positrons are extracted from the PAR at a 2-Hz rate, and are transported to a booster synchrotron where the energy is increased to 7 GeV. The 7-GeV beam is transported to the 1104-meter-circumference storage ring, where it circulates with a lifetime of at least 10 hours, corresponding to at least 10^{10} revolutions. The positron current decreases with time due to beam interactions with the residual gas. Beam is reinjected into the storage ring from the injector as required. Figure 4 is a schematic view of the APS accelerator systems showing the linac, PAR, booster synchrotron, and the storage ring. Beam diagnostics, such as current monitors, fluorescent screens, and beam position monitors allow beam parameters in all machines to be accurately measured and optimized.

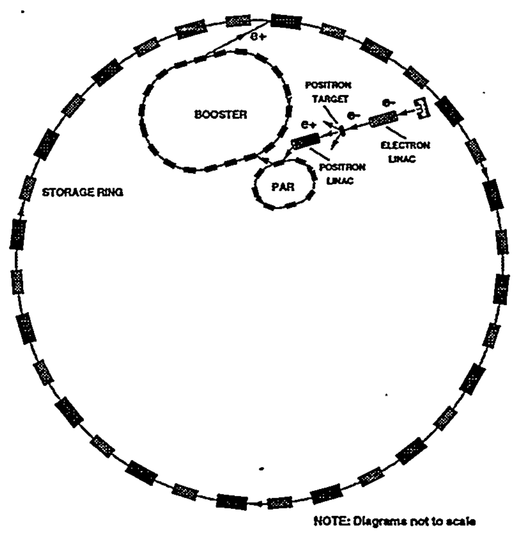

Figure 4: Schematic view of the APS accelerator systems [not to scale].

The storage ring and experiment hall, shown in Figure 5, are divided into 35 sectors. Each sector is managed by the scientists in one of the APS Collaborative Access Teams (CAT), in effect creating a multitude of individual laboratories at one facility. Each sector has two beamlines extending tangentially from the storage ring enclosure onto the floor of the experiment hall, as shown in Figure 6. One beamline in each sector originates from a bending magnet. Bending magnet radiation has a broad energy distribution. The other beamline originates from an insertion device (ID). Insertion devices, such as undulators or wigglers, are linear arrays of permanent magnets arranged such that the magnetic field directions alternate as shown in Figure 7, and they are central to the enhanced capabilities of the APS. As the positron beam passes through the alternating magnetic fields of an undulator, the electromagnetic forces cause it to oscillate and produce very high brilliance synchrotron radiation. Figure 8 shows the anticipated spectral brilliance of x-rays from several types of insertion devices at the APS. The x-ray beams are focused and refocused by mirrors and made monoenergetic by monochromators before they illuminate the sample being studied. The very high power densities of undulator radiation, shown in Figure 9, require use of special monochromator materials such as diamond and innovative cooling techniques in order for the optical elements to withstand the high heat loads.

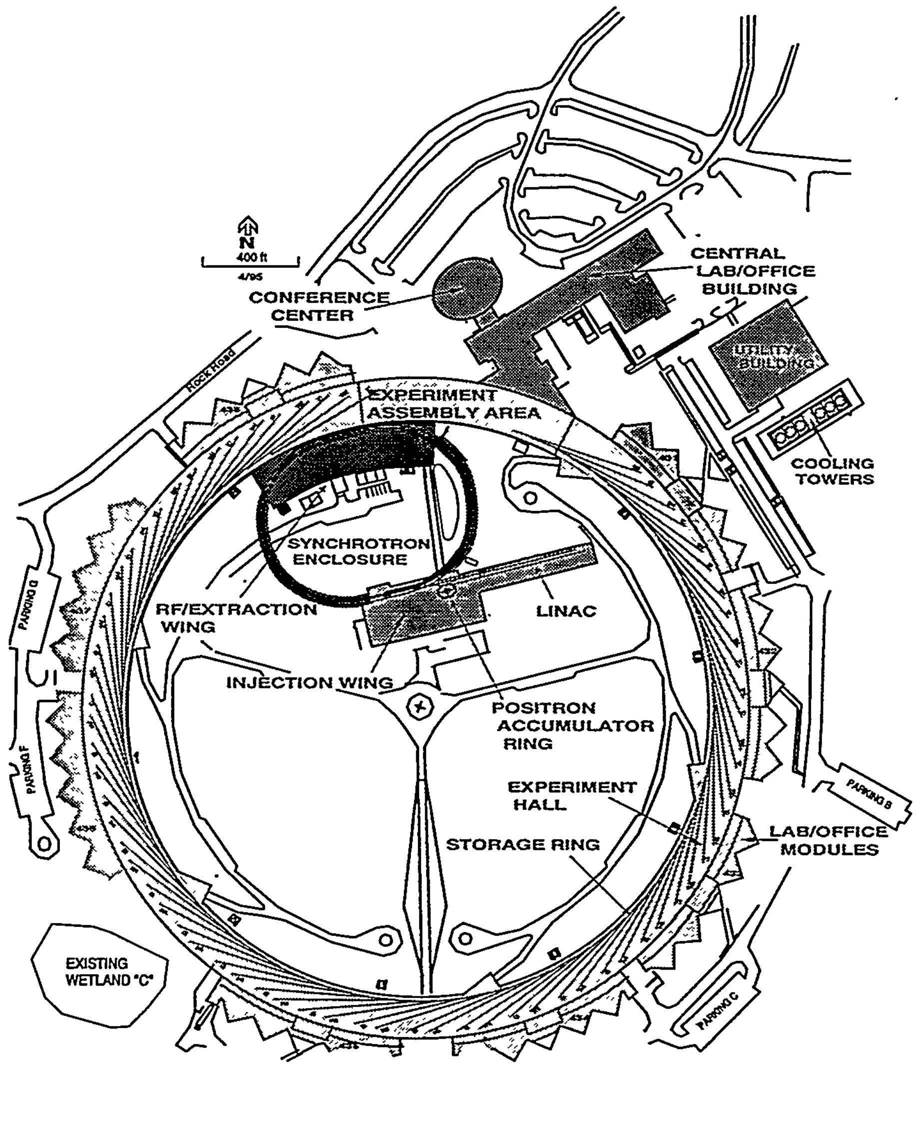

Figure 5: Plan view of the APS.

One Sector of the Advanced Photon Source Storage Ring

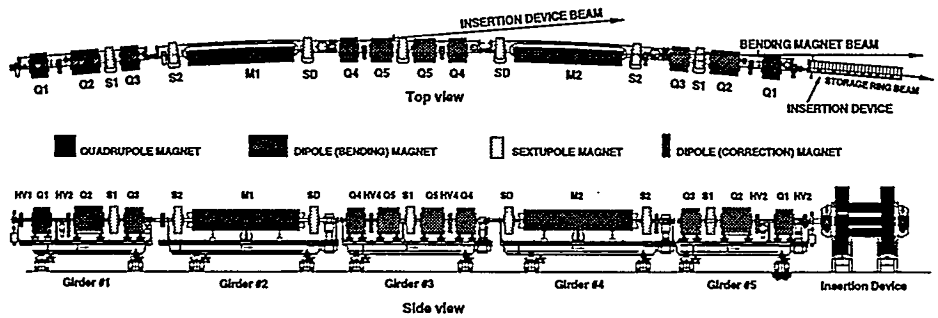

Figure 6: One sector of the storage ring, showing origins of the beamlines.

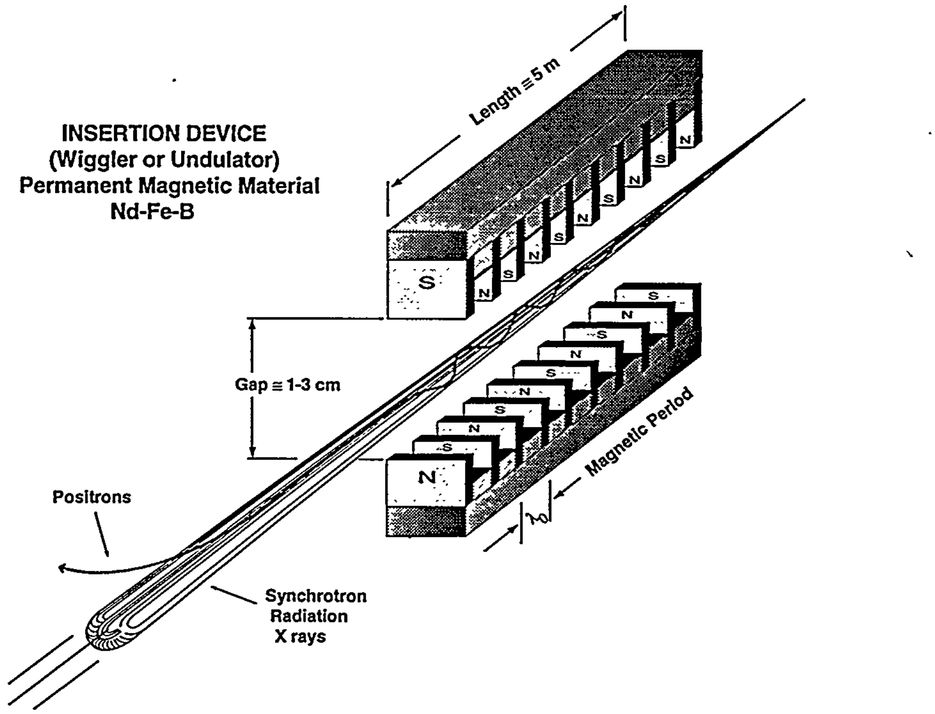

Figure 7: Synchrotron radiation is produced by the particles passing through the undulator's alternating magnetic field.

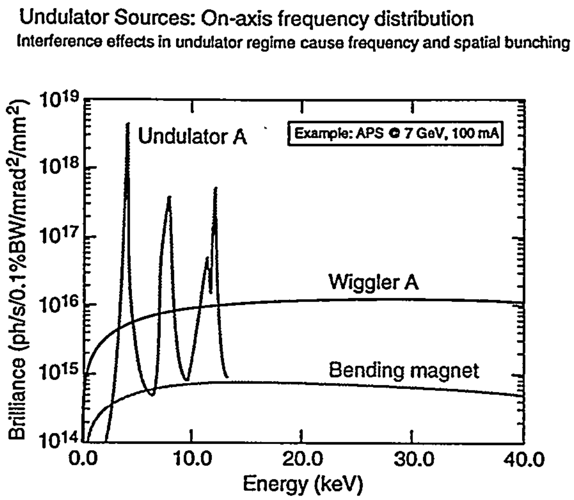

Figure 8: Spectral brilliance from different IDs at the APS.

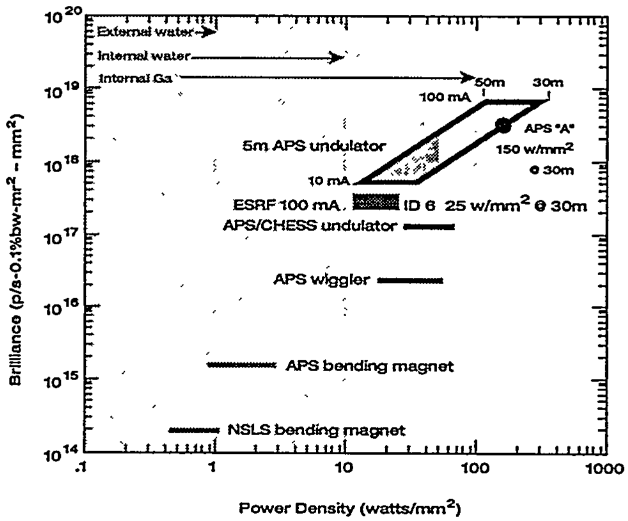

Figure 9: X-ray power densities for different ID's.

III. EXPERIMENTAL PROGRAM

Synchrotron radiation wavelengths are of the order of 10^{-1} to 10^{3} angstroms. Sizes of atoms, molecules, and proteins, lengths of chemical bonds, and minimum distances between atomic planes in crystals are within that range. These wavelengths are ideal for studying the atomic structure of solids, molecules, and biological structures. The photon energies range from a few electron volts to 10^{5} eV, corresponding to binding energies of electrons in atoms, molecules, solids, and biological systems. Synchrotron radiation x-rays have the right energies to probe chemical structures. Mechanical characteristics, optical responses, and electric transport properties of solids, as well as physical and chemical properties in general, can all be better understood with detailed knowledge of the electronic structure of the systems under study. The high brilliance available at the APS will enable data for many experiments to be collected in fractions of a second instead of years.

Geophysical high-pressure experiments can be performed using a diamond anvil such as that shown in Figure 10 to study the formation of the earth's crust. A small amount of material, on the order of 1-10 μm is crushed with high pressure (500 GPa) and heated to high temperatures (3400 °C) with a laser. Changes in the material can be observed by means of x-ray diffraction.

Time evolution of systems can also be studied, since the synchrotron radiation is emitted by each of the positron bunches as they circulate past the ID. The number of bunches in the storage ring, and thus the time spacing between them, can be varied from one bunch that circulates every 3.5 μsec to multiple bunches with shorter inter-bunch spacing. The length of an individual bunch is about 116 psec which is a limit to the ultimate resolution. Many interesting reactions, from catalytic reactions that take place over periods of seconds to faster reactions that take place in microseconds and less, can easily be studied.

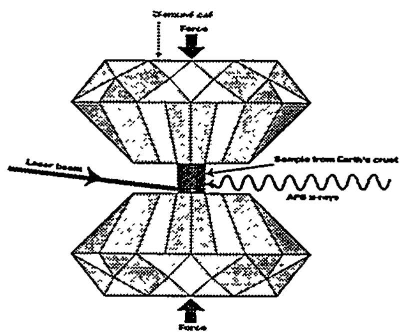

Figure 10: Diamond anvil cell.

IV. CONCLUSION

The APS accelerator systems and experimental facilities are now in the commissioning phase [3], and will soon be ready to support a very exciting experimental program.

V. REFERENCES

[1] 7-GeV Advanced Photon Source Conceptual Design Report, ANL-87-15, April 1987.
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