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SYNCHROTRON RADIATION*

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ABSTRACT

Synchrotron radiacion has had a revolutionary effect on a broad range of scientific studies, from physics, chemistry and metallurgy to biology, medicine and geoscience. The situation during the last decade has been one of very rapid growth, there is a great vitality to the field and a capability has been given to a very broad range of scientific disciplines which was undreamt of just a decade or so ago.

Here we will discuss some of the properties of synchrotron radiation that makes it so interesting and something of the sources in existence today including the National Synchrotron Light Source (NSLS). The NSLS is one of the new facilities built specifically for synchrotron radiation research and the model that was developed there for involvement of the scientific community is a good one which provides some good lessons for these facilities and others.

SYNCHROTRON RADIATION

In any scientific discipline, specifically the experimental scientific discipline; the frontiers of the science are defined by our capabilities. Synchrotron radiation has given us a revolutionary capability over a very broad spectral range to do studies of structure, properties and phenomena of materials. Synchrotron radiation is one of the most versatile of the electromagnetic sources, it has many of the ideal properties one would design into a radiation source.

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We started in the late 1960's and early 1970's with the use of bending magnetic radiation from high energy physics electron storage rings. We then introduced the first insertion devices on these machines, and buoyed by early successes, developed machines dedicated to synchrotron radiation and which were designed to optimize source brightness.

Before the late 1960's and early 1970's we were confined to the use of the so-called labs sources, that is Bremmstrahlung sources and line sources which are limited in their performance by the ability of target materials to absorb power.

The figure of merit for a radiation source is the spectral brightness. A bright spectral source has the quality that the effective source size is small, the radiation is emitted into an intrinsically small solid angle and that there is a large number of photons per unit energy and per unit time. The standard units for brightness are

$$\text{Photons/sec} \cdot \text{mm}^2 \cdot \text{mrad}^2 \cdot .1\%\text{Bandwidth}$$

In these units the best "lab" sources produce a brightness of approximately 10^8. The first use of bending magnet radiation from existing synchrotrons in the late 1960's and early 1970's brought us an improvement of 3 to 4 orders of magnitude in brightness, bringing us to the 10^{12}-10^{14} level. The second generation machines, those built in the late 1970's specifically for synchrotron radiation research, are designed to optimize electron beam current and electron beam brightness, and the intrinsic brightness of the photon beams from bending magnets. The installation of "insertion devices," wigglers and undulators, can add another factor of 10 to 10,000 over the brightness of a bending magnet on the first two generation machines, bringing us to 10^{12} to 10^{14} on first generation machines and to 10^{14} to 10^{17} on second generation machines.

Around the world there is a move to produce yet another generation of storage rings which is based on very high brightness electron beams and the use of undulators and that will bring us yet another two to three orders of magnitude in brightness, bringing us to the 10^{19} to 10^{20} range! An important thing to realize throughout this progression is that in any experimental measurement when you can achieve a factor of two improvement in any quantity, it usually leads to some quantitative difference in the nature of the science you can do. What we see in synchrotron radiation is that we have gained on the average of an order of magnitude every two years or so for the last decade and a half and it has had a phenomenal impact on the science we do.

The involvement in synchrotron radiation is worldwide. There are now over a dozen sources around the world. There are seven in the USA with several in Europe, several in Japan, three in China that are now being constructed, and the community continues to grow. There are several next generation rings being built. In the USA the Advanced Light Source is being built at Lawrence Berkeley Laboratory to study the soft X-ray region of the spectrum, and the Advanced Photon Source is to be built at Argonne National Laboratory, to provide bright beams in the X-ray region. In Europe the ESRF is being built at Grenoble to cover the X-ray region, and two machines, BESSY II in Berlin and a machine in Trieste, which cover the same spectral range as the Advanced Light Source at Berkeley. In Japan a number of efforts are underway to produce third generation machines as well as industrial sources for use by the semiconductor industry in X-ray lithography. And of course, the machine which is now being constructed in Brazil will produce radiation across the entire spectrum.

THE PROPERTIES OF SYNCHROTRON RADIATION

In a storage ring an electron beam has an energy

$$E = \gamma mc^2$$

In the bending magnet the electron beam is bent in an arc of radius R. While the electrons path is being bent, it emits synchrotron radiation. That synchrotron radiation has an intrinsic opening angle, $\delta = 1/\gamma$ and is distributed continuously in energy. It has a critical wavelength, λ_c, which defines the half power point, i.e. half the power is above that wavelength and half below, given by

$$\lambda_c = \frac{R}{\gamma^3}$$

A typical synchrotron, of say, E = 3 GeV, (γ = 6000) and a bending radius R $\approx$ 20 meters, gives us a critical wavelength of approximately an Angstrom. One Angstrom wavelength is important because one Angstrom is nominally the interatomic space in solids and molecules. To study atomic structure of materials a wavelength of the order of one Angstrom is most appropriate. The opening angle of the X-ray beam is very small, roughly forty seconds of arc and the radiation is highly polarized in the plane of the electron orbit.

We can achieve further increases in synchrotron radiation by using what are called insertion devices. An insertion device is a complex magnetic device which is inserted in straight sections of the electron storage ring. The insertion device produces a vertical magnetic field which is modulated along the path of the electron beam, which causes the electron beam to oscillate in a horizontal plane around its straight line path through the device. As it oscillates it continually emits radiation in the forward direction into a horizontal opening angle equal to the electrons angle of deviation from its straight line path. There are two types of devices designed around this effect. The first is the so-called wiggler. In a wiggler, the path of the electron is deflected far more than the intrinsic opening angle of the radiation $1/\gamma$. The parameter K is the ratio of the ratio of the angular deviation of the beam to the intrinsic $1/\gamma$, so a wiggler has K >> 1. A wiggler produces a linear gain in source brightness which is proportional to the number of poles in the device. A wiggler spectrum can be controlled in two ways, 1) increasing the number of wiggles (poles) in the device increases the brightness of the radiation and 2) controlling the magnetic field separately from the optical function of the lattice controls the critical energy.

A more sophisticated device is the so-called undulator. In an undulator, the electron beam wiggles at an angle less than the intrinsic opening angle, $1/\delta = 1/\gamma$. In an undulator, constructive interference between radiation emitted in successive oscillations of the electron beam results in a spectrum which is not continuous, but which has sharp peaks located at energies characteristic of the insertion device. The device emits a fundamental energy given by

$$E_1 = \frac{0.95\ E^2\ (GeV)}{\lambda_u(cm)(1+K^2/2)}$$

and harmonics of the fundamental. Here λ_u is the period of the undulator and K defined above. The spectral width ΔE of the peaks are approximately

$$\frac{E}{\Delta E} \alpha \sqrt{N} \quad \text{when N is the number}$$

of poles in the device. The radiation is emitted ideally into an opening angle $\delta_n \alpha \frac{N}{\gamma\sqrt{N}}$. The total gain in brightness goes like N^2 for an undulator as opposed to N for a wiggler. Storage rings which make optimum use of undulator radiation must have two properties: 1) A higher energy electron beam because the characteristic radiation energy is proportional to E^2 rather than E^3 of a bending magnet or wiggler and 2) an intrinsic <u>electron beam</u> emittance which is less than the intrinsic <u>photon beam</u> emittance of the undulator. (The emittance ϵ is proportional to the product of the beams effective source area A and its opening angle Ω, $\epsilon \alpha A\Omega$.) The ALS at Berkeley and the APS at Argonne have their design energies and electron beam emittances aimed at optimum undulator radiation in the soft X-ray and X-ray regions respectively, leading to the choices of 1-2 GeV and 7 GeV respectively.

THE USES AND USERS OF SYNCHROTRON RADIATION

Synchrotron radiation has made a qualitative difference in the experimentation of virtually every discipline it has touched. Surface science has profited from many generations of photoemission and soft X-ray absorption experiments, yielding information on the electronic and atomic structure of surfaces of interest in electronics, catalysis, and metallurgy among others. The semiconductor industry has developed X-ray lithography which could provide a new technological impetus to the industry in the 1990's as the Gigabit chip is approached! Soft X-ray microscopy has looked into living cells with high contrast and X-ray holograms have been taken of subcellular structures, pointing to important new areas of experimentation. X-ray scattering has been applied to surfaces, interfaces, weakly scattering systems, such as magnetic systems, and exotic materials, such as quasicrystals. Crystallography has moved to exquisite structure refinements and the study of micron size crystals, rapid determinations of the structure of extermely small and delicate biological crystals, and continues to push spatial and temporal boundaries of study. X-ray absorption, which was really made feasible with the advent of synchrotron radiation, has been applied to uncounted systems for the determination of local atomic order, and is now being pushed to new limits of atomic, spatial, and temporal resolution.

All of these areas of study make synchrotron radiation research attractive and useful to a wide range of researchers from Universities, Industry, and various Government laboratories. Synchrotron Radiation facilities are generally government sponsored and are provided free of charge to qualified users. The National Synchrotron Light Source at Brookhaven National Laboratory in New York, USA was built by the US Department of Energy to make synchrotron radiation available to the widest possible community of scientists. At the NSLS Participating Research Teams made up of Industrial, Academic, and Government scientists establish extensive experimental programs based on their own resources in the form of beamlines specifically designed and built by the teams for their own research. The facility provides X-ray beams and other services as part of it's overall operating mandate from the DOE. In return, the PRT's provide for use of their experimental resources by the general community of synchrotron radiation users, so that the entire resource of the commuity is available to everyone. This mode of operation has led to the establishment of nearly 100 bemalines which individually and collectively represent the state of the art in our science. It is an important model for consideration by any emerging facility.