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S-E-1

# Applications of Synchrotron Radiation to Material Characterization

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Because synchrotron radiation (SR) sources possess a number of significant advantages over ordinary laboratory sources, advantages such as high intensity, high degree of beam collimation, small source size, and wavelength tunability, many new fieilds in science and technology have opened up since it first came into general scientific use. It is timely to review the development of new x-ray optics, new characterization techniques using SR, and some other related applications.

## 1. CHARACTERISTICS OF SYNCHROTRON RADIATION SOURCES

As is widely known, SR (synchrotron radiation) is a quite powerful and straight forward-directed light source emitted by the moving electrons or positrons in a circular orbit under a high vacuum condition. Its divergence is the order of $mc^2/E$, where $mc^2$ is the rest energy of the electron and E the energy of moving electrons. The critical photon energy of the spectrum available from bending magnets is 4 KeV in case of the Photon Factory (PF) ring and 20 KeV for the Accumulation Ring (AR). The superconducting vertical wiggler of the PF provides almost the same spectrum as that of AR. Insertion devices (ID), which are arrays of permanent magnets such as Neomax along the electron orbit in the straight section, can provide quasi-monochromatic light both in the vertical and horizontal direction. The degree of monochromatization and the intensity for the even orders are dependent on the emittance, which is defined as the product of the size and the divergence of the electron beams. Most of the work which will be described later have used bending magnet sources of the PF, whilst for soft x-ray microscopy an undulator source was used at BL 2, and for intravenous coronary angiography the bending magnet source NE5 of the AR (Accumulation Ring) was used. Those spectra are shown in Fig.1.

## 2. X-RAY OPTICS

In designing x-ray optics for monochromatization and collimation we use concepts founded in the principles of x-ray optics (Ref.1). Since SR (synchrotron radiation) has its own natural divergence of

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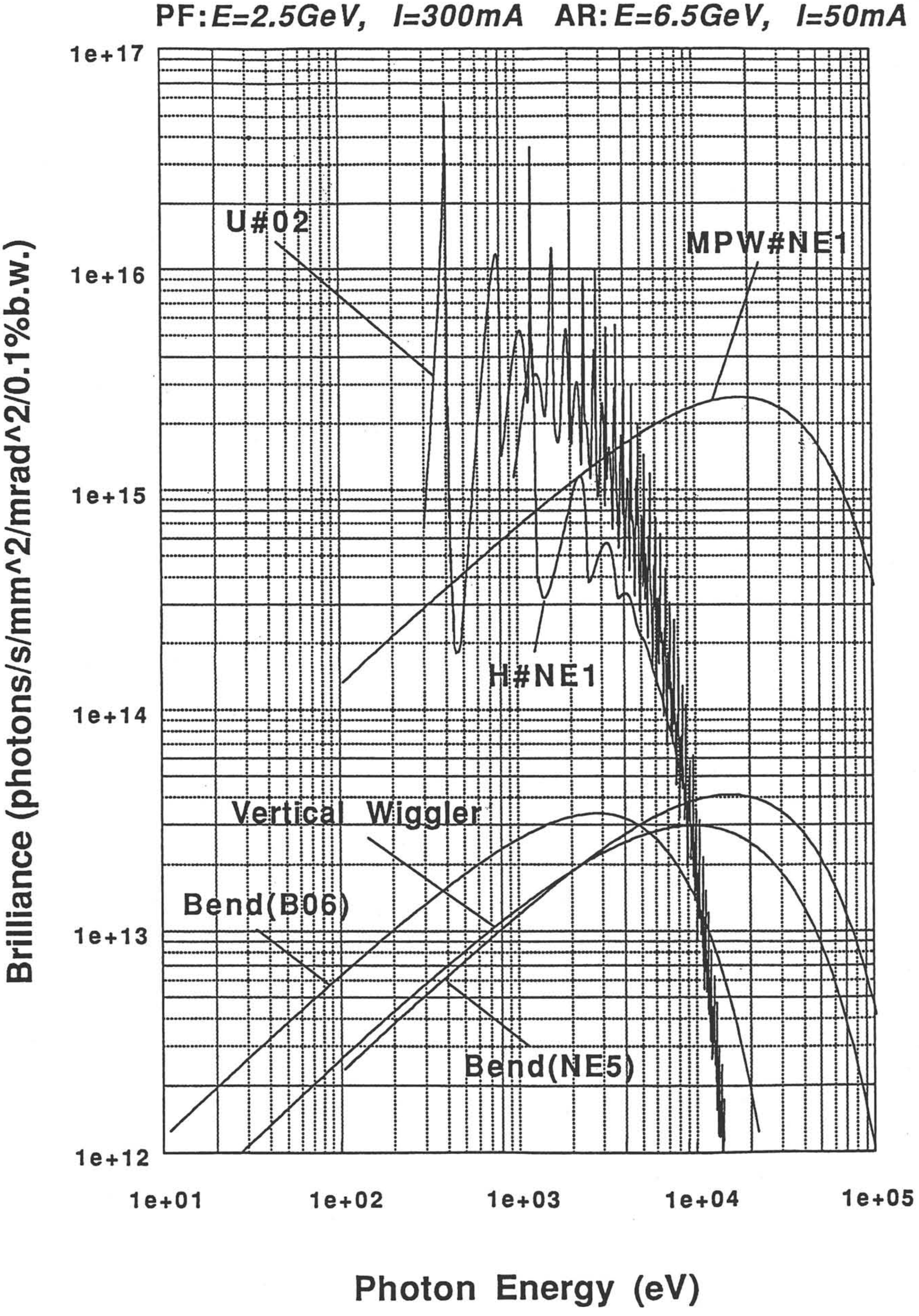
PF: E=2.5GeV, I=300mA AR: E=6.5GeV, I=50mA
1e+17
1e+16
1e+15
1e+14
1e+13
1e+12
U#02
MPW#NE1
H#NE1
Vertical Wiggler
Bend(B06)
Bend(NE5)
Brilliance (photons/s/mm^2/mrad^2/0.1%b.w.)
1e+01
1e+02
1e+03
1e+04
1e+05
Photon Energy (eV)

Fig.1 Spectrum of SR available from the 2.5 GeV PF storage ring and the 6.5 GeV AR accumulation ring. Bend: bending magnet source; U: PF undulator; H: AR undulator for completely circularly polarized SR; MPW: AR multipole wiggler; Vertical Wiggler: super conducting waveshifter for high energy x-ray photons.

the order of 4-40 arc seconds in the x-ray and soft x-ray energy ranges, one can easily, in practice, make the photon beam quite parallel by use of asymmetric diffraction techniques say, currently up to of the order of 0.001 seconds of divergence (Ref.2). As well, the electron beam size in the orbit and the above-mentioned divergence creates an effective beam size at the sample position as follows,

$$\delta = \sigma + L * \sqrt{(\sigma_e'^2 + \sigma'^2)} \quad (1)$$

where $\delta$ is the photon beam size, $\sigma$ FWHM of the electron beam size, L the distance between the source and the sample, $\sigma_e'$ the divergence of the electron beam and $\sigma'$ the divergence of the photon beam. Further, the spatial resolution of image is determined from the source size $\sigma$, the distance L, and the distance $\iota$ between the sample and an imaging plane. The so-called first generation of SR sources have a relatively larger source size so that it is at present not easy to obtain a submicron order of spatial resolution unless either proximity projection or focussing optics is used. $\delta$ the source size will be projected onto the image plane with the size d shown as follows,

$$d = \delta * \iota / L \quad (2)$$

Since $\delta$ ranges in the order of a few millimeters, one can easily achieve submicron of d under the proximity projection where if $\iota$ /L is taken as 0.0001. This has, for instance, application to SR lithography which are currently being developed. In the other imaging fields where a smaller beam size onto a sample is needed, a variety of focussing optics have been tried and are still under development (Ref.3). It seems fairly difficult to accomplish focussing with the size smaller than one micron in each dimension because of the problems caused in the construction of optical elements. In the next generation of SR sources whose emittance will be of the order of nanometer · rad (Ref.4-6) the beam size will certainly be required to be smaller than 1000 Å.

## 3. Applications

Extension of a variety of applications of SR is even under acceleration : that is observably in the field covering from VUV to x-rays industry oriented utilization to purely basic research, not only inorganic materials but also biological specimens. All utilize the advantages of SR - its intensity, energy tunability, parallelity, small source size, polarization and pulse structure.

Emphasis will be on the imaging techniques such as x-ray lithography, x-ray diffraction topography, x-ray fluorescence imaging, x-ray photoacoustic imaging, soft x-ray microscopy, Crystals of proteins and macromolecules are characterized by fairly large unit cell dimensions such as 10-1000 angstrom and quite often smaller crystal size such as ten microns. Further these crystals dislike radiation damage. Under the current instrumental development and improvement, one can achieve an exposure time down to sub microseconds which will lead us to time-resolved crystallography, aiming at the explicit determination of transient structural intermediates such as forming and decaying chemical bonds in the crystals.

Crystals viewed from those lattice spacing are going to be more precisely characterized. The lattice spacing variation dependent on crystal growth are now uniquely understandable in terms of internal stress.

It is almost needless to say about EXAFS and XANES that has become quite a fundamental tool not only to observe basic structure problems of the matters but even to develop any electronic materials.

Not only having material characterization by means of x-ray diffraction based on k-space but also in the near future that by the technique of momentumn space such as Compton scattering will be undertaken.

Since alredy a complete circularly polarized SR has been successively produced at PF, new fields should be opened.


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