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Physics and Technology Challenges of Ultra Low Emittance Synchrotron Light Sources*

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Abstract

There is great activity throughout the world in the development of synchrotron radiation facilities to serve as sources for basic and applied research. We discuss some of the opportunities and challenges presented by the development of ever higher brightness synchrotron radiation sources.

I. INTRODUCTION

It is very exciting to observe the rapid worldwide development of synchrotron radiation facilities [1]. Although synchrotron radiation research began parasitically on synchrotrons and storage rings designed and operated for high energy physics, over the last decade a second generation of storage rings were brought into operation as dedicated synchrotron radiation sources. In order to provide higher brightness [2,3] photon sources, these second generation machines had lower electron emittances [4] than the high energy physics storage rings, and had long zero dispersion straight sections for the placement of wiggler and undulator magnets [5]. Presently a third generation of facilities are under construction promising even higher brightness photon sources utilizing even lower emittance storage rings.

The operating facilities are now providing photons to thousands of researchers working in diverse areas of the basic energy and life sciences. Industrial research is an important component of the activities at these facilities, and in particular the development of X-ray lithography [6] has stimulated great activity as a potential technique for the development of higher performance integrated circuits for computer systems. Utilization of synchrotron radiation angiography [7] of the human heart is an enterprise that may be expected to increase in importance over the next decade.

The widespread use of synchrotron radiation is due to its unique properties. It is in fact the most versatile of EM sources, offering:

- High intensity over broad spectral range
- High brightness
  - Small angular divergence
  - Small source size
- Temporal coherence (tunable wavelength utilizing monochromator)
- Spatial Coherence (pinhole as spatial filter)
- Pulsed time structure
- Polarization

High intensity and high brightness have been of central importance in the development of high resolution studies of small samples, surfaces and interfaces. The broad spectrum of synchrotron radiation has allowed the development of extremely diverse experimental programs utilizing the same facility. High temporal coherence is achieved with monochromators utilizing crystals (X-rays), gratings (ultraviolet) and interferometers (infrared). The ability to continuously tune the wavelength using the monochromator has opened up new scientific opportunities not possible using conventional line sources. Experiments requiring spatial coherence have been carried out using a pinhole as a spatial filter. In this manner holograms at 30Å have been made. High intensity together with the pulsed time structure of the radiation allows the study of time dependent phenomena in physical and biological systems. The polarization of the source is employed in the study of magnetic systems and e.g. in investigations of the dichroism of large helical molecules.

The new synchrotron radiation facilities place increasing emphasis on the use of wiggler and undulator insertion devices [5]. Wiggler and undulator magnets are comprised of a linear array of magnetic poles alternating in polarity. Since they produce local deflection, but no net deflection, radiation from these devices is predominantly confined to a small solid angle about the axial direction. This results in a large increase in the photon flux per unit solid angle. An insertion device is called a wiggler if the angular deflection of the electron beam at each pole is large compared to the instantaneous emission angle ($1/\gamma$) of synchrotron radiation.

The wiggler source consists of a succession of bending magnet sources, producing a broad spectrum characterized by the cut-off wavelength $\lambda_c \propto \rho/\gamma^3$, where ρ is the bending radius corresponding to the peak wiggler magnetic field, and γ is the electron energy in units of the rest mass. An insertion device is called an undulator if the deflection angle in each pole is less than or comparable to $1/\gamma$. In this case the radiation spectrum is dominated by a few harmonics of the fundamental mode, whose wavelength in the forward direction is $\lambda_1 = (\lambda_w/2\gamma^2)(1+K^2/2)$, where K/γ is the maximum horizontal deflection angle.

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To generate short wavelength radiation leads one to high electron energy. High source brightness requires small electron emittances. The horizontal emittance in a storage ring has the dependence $\epsilon_x \propto \gamma^2 \theta_D{}^3$, where θ_D is the bend angle per dipole. Therefore, low emittance at high energy requires small θ_D, hence a ring which is comprised of many short dipoles separated by a large number of strong quadrupole magnets for electron focusing. It follows that a low emittance storage ring has large circumference, made even larger by providing many long straight sections for insertion devices. This means higher brightness leads to higher cost.

Third generation sources [1] for the soft X-ray and ultraviolet regions of the spectrum are being built utilizing electron energies from 1-2 GeV. Among these we might mention the ALS at Lawrence Berkeley Lab, ELETTRA at Trieste, Italy, SRRC, Taiwan and Pohang Light Source in Korea. Third generation sources [1] for hard X-rays are: the APS (7 GeV) at Argonne Lab, the ESRF (6 GeV) at Grenoble, France, and Spring8 (8 GeV) in Japan. All of these are designed to have horizontal electron emittance $\epsilon_x \leq 10^{-8}$ m-rad and undulator brightness $\sim 10^{19}$ photons/sec, 0.1% $\Delta\lambda/\lambda$, mm^2, mrad^2.

Consideration is already being given to going to even lower emittance [8,9] say 10^{-9} or 10^{-10} m-rad. In fact, the large e^+-e^- colliders, PEP, PETRA and TRISTAN are already operating for high energy physics. If, in the future, these rings became available in a dedicated fashion for synchrotron radiation research, they could be run well below their design energies, say at 6-10 GeV, with emittances $\lesssim 10^{-9}$ m-rad. This is a very exciting possibility, especially since these rings have very long straight sections (~ 100 m) which could be used for insertion devices, and possibly even free electron lasers.

II. IMAGING

As an example of an experiment requiring high source brightness, let us consider focusing the source to a small diffraction limited spot. For a given full source size, S, the acceptance angle for coherent illumination of the lens is θ_{ACC} determined by

$$S\theta_{ACC} \leq \lambda$$

where λ is the wavelength of the radiation. The diffraction limited full spot size is given by

$$D_{MIN} = \lambda/N.A.$$

where N.A. is the numerical aperture of the lens. For a given source size S, illuminating the lens by radiation emitted into an angle larger than θ_{ACC} does not help, since in this case the lens will no longer be coherently illuminated and the achievable spot size will be increased over the diffraction limited value D_{MIN}, resulting in a loss of spatial resolution. Therefore, the figure of merit is the source brightness, i.e. the number of photons emitted per sec, per unit source area, per unit solid angle, per unit spectral bandwidth $\Delta\lambda\backslash\lambda$.

There is presently great activity in the development of soft X-ray microscopy [10]. Of special interest is the use of radiation in the "water window" between the carbon and oxygen absorption edges, since it facilitates good absorption contrast for aqueous biological specimens. The relatively small penetration depth has also made the soft X-ray wavelengths very useful for surface microscopy. Recent advances in the development of a scanning photoemission microscope allows the study of the composition of the surface.

A zone plate is used to focus the soft X-rays, and its resolution is also approximately the radiation wavelength divided by the numerical aperture. For the zone plate the numerical aperture is a function of wavelength, and the resolution turns out to be given by the width of the finest (outermost) zone. Resolutions in the range of 0.1 μm have been achieved, and it is believed that extension of present techniques will lead to 0.05 μm resolution in the near future. Imaging will be an important component of the experimental program on the 1-2 GeV third generation rings. The new sources will not improve the resolution for a given optics, but will substantially reduce the required exposure time, increasing the applicability of soft X-ray microscopy as a research tool.

III. ORBIT STABILITY

A necessary condition for realizing the full potential of a high brightness radiation source is a very stable electron orbit. For example, suppose the vertical emittance to be 10^{-9} m-rad. If at the undulator source $\beta_y = 10$ m, then the electron beam size and angular spread is

$$\sigma_y = 100\ \mu\text{m} \ \text{ and } \ \sigma_y' = 10\ \mu\text{rad}$$

It is natural to demand that neither the source size nor angular spread be increased by orbit motion by more than 10%. In this case the tolerance on the orbit becomes

$$\Delta y < 10\ \mu\text{m} \ \text{ and } \ \Delta y' < 1\ \mu\text{rad}$$

The ambient orbit motion due to ground vibrations, thermal effects, power supply ripple, etc. may be expected to exceed these limits. Moreover, some experiments will require even tighter tolerances. To proceed, one must first develop electron beam and photon beam position monitors [11] capable of a precision of a few microns. Great progress has been achieved in this direction [12-14]. Of critical importance in the development of these monitors is that they give position readings independent of electron current or photon intensity, and that they have high long term stability.

Pick-up electrode or stripline signals can be processed either in the time or frequency domain. Working in the time-domain, Pellegrin and Hayano [13] have achieved 1 μm resolution at the SLC. Single turn resolution of the electron orbits can be of use in studies of injection, instabilities or local

transverse coupling, however, for most synchrotron radiation experiments a bandwidth of < 1 KHz is adequate. Bittner and Biscardi [14] have developed RF receivers with rms noise corresponding to 5 μm over a bandwidth of 300 Hz.
Operation over a large dynamic range of ring current was achieved by selecting one Fourier component of the pick-up electrode signals and "time sharing" a single amplifier and detector among the four electrodes of a single station, thus eliminating the need to precisely match the gain of amplifiers for the four channels.

Orbit feedback can be used to reduce the ambient orbit motion to within the allowed tolerance. Global systems [15] stabilizing the entire ring and local systems [16] stabilizing a single experiment have been successfully operated. A key issue which will have to be addressed at the third generation facilities is the requirement of changing insertion device magnetic field strengths within a fill without producing observable orbit motion.

IV. HIGH POWER DENSITY ON OPTICAL ELEMENTS

Even though undulators provide high brightness with relatively low total power, the power density in the radiation beam is very high. For example the APS undulators will produce power densities up to 300 watts/mm^2. Such high power densities will cause local heating which can produce local distortion of optical elements in the X-ray beamline. Of particular concern is distortion of the first crystal in a monochromator. Such distortion can produce a reduction of angular resolution with increasing photon intensity, to the extent that the output of the monochromator within a given spectral bandwidth can cease to increase with electron current.

R&D on crystal cooling has been pursued at the operating synchrotron radiation facilities. Significant recent progress has been made. One elegant approach is the cryogenic cooling [17] of X-ray silicon monochrometers or mirrors. At cryogenic temperatures silicon's thermal conductivity increases as the temperature decreases, and the coefficient of thermal expansion decreases and goes through zero at 125°K. The difficulty is removing high heat loads in a cryogenic system. However, recent success with liquid nitrogen cooling by the ESRF group [17] on the NSLS X25 focused wiggler beamline (75 watts total power, 150 watts/mm^2) is stimulating further work in this direction.

The APS group [18] has pioneered the development of liquid gallium cooling via channels cut close to the crystal surface. Berman and Hart [19] have had success using a directly water-jet-cooled thin wall silicon hollow box, in which local distortions are canceled by applying an external mechanical stress or by varying the pressure of a helium atmosphere.

V. HIGH TEMPORAL COHERENCE

There has been recent interest in exciting the ultranarrow Mossbauer resonance by nuclear photoabsorption using synchrotron radiation [20-22]. In ^{57}Fe the resonance occurs at 14.413 KeV and has a bandwidth of 10^{-9} eV. In order to overcome the signal to noise problem in detecting the small number of photons within the resonance bandwidth, a new monochromator was developed [21] which provided an energy resolution of 5x10^{-3} eV and an angular divergence of 0.4 arc seconds at 14.413 KeV. With the output of the monochromator incident upon a highly perfect crystal of ^{57}Fe$_2$O$_3$, the nuclear resonant photons were detected with a signal to noise ratio of 100:1 relative to the synchrotron continuum. A large fraction of the unwanted electronic scattering was suppressed by arranging the resonant atoms in the crystal lattice such that for the Bragg reflection of interest only the resonant nuclei scatter in phase.

When this experiment was performed on an NSLS bending magnet, 1 count/sec was detected. Using the CHESS wiggler, the rate was increased to 15 counts/sec. Later, an experiment [22] utilizing the PEP undulator observed 500 counts/sec. More recently, employing an undulator on the TRISTAN Accumulator Ring, 10,000 counts/sec were detected. This is a dramatic demonstration of how the development of increasingly intense sources is transforming experimental techniques which can only be accomplished as tour de force demonstrations on second generation rings into new research tools available to users on the brighter sources now under development. It also highlights the importance of instrument R&D on the existing operating facilities. The nuclear Bragg diffraction studies carried out to date require high collimation of the source, but not the full brightness. However, future experiments may be carried out focusing the radiation onto very small crystals, in which case small source size would be necessary and hence high brightness would become the figure of merit of the source.

VI. A TUNABLE INFRARED SOURCE

The development of infrared beamlines on the NSLS VUV-Ring [23] and on UVSOR in Japan [24] provide striking examples of the importance of tunability of the radiated wavelength. The infrared beamlines operate in the wavelength region of 10-1000 μm, and although there exist conventional laser sources with peak power 10^5-10^7 times as high as the synchrotron source, the availability of the infrared beamlines has opened up new experimental opportunities [25]. In particular, the first measurement of molecule-substrate vibrations in surface science and of the transmission of a film of high-T$_c$ superconducting material YBaCuO in the BCS gap region have been made. To carry out these spectroscopic measurements easy, rapid tunability of the radiation wavelength was necessary.

The reason for the utility of the infrared synchrotron source is that it is 100-1000 times brighter than black body sources, easily tunable and very quiet. By quiet it is meant that the intensity vs. time has small fluctuation. On the NSLS beamline IR4 the intensity fluctuation has been observed to be only 0.006%, over a time interval of 80 sec, after the elimination of 360 Hz ripple from the ring dipole power supply and the installation of the vertical global orbit feedback system [15]. A storage ring is inherently a very quiet source since the number of electrons in the circulating beam changes very slowly. Conventional lasers are very intense, but not easily tunable and exhibit significant pulse-to-pulse intensity fluctuation.

VII. PULSED TIME STRUCTURE

The pulsed time structure of synchrotron radiaton makes possible the study of time dependent phenomena in physical and biological systems. As an example, at Cornell [26] an X-ray Laue pattern of a protein was obtained in a 1 nsec exposure from the radiation emitted by a single bunch passing through the APS/CHESS undulator. As higher and higher peak power becomes available at the new facilities, the study of dynamic phenomena can be expected to grow in importance.

To this point in our discussion we have considered incoherent synchrotron radiation emitted independently by individual electrons, with intensity proportional to the number of radiating electrons. However, in the case when the bunch length is shorter than the radiation wavelength, there will be coherent emission with intensity proportional to the square of the number of electrons in the bunch. Although coherent emission has not yet been observed from a storage ring, coherent synchrotron radiaton was recently observed [27] by passing through a bending magnet 180 MeV short electron bunches of 2.5 mm length from the Tohoku linac. Quadratic dependence of the synchrotron radiation intensity on electron current was measured in the wavelength range 0.4-2.2 mm, with an enhancement in peak intensity of about 10^5 over the incoherent radiation. Coherent emission has recently also been observed [28] using the Cornell linac.

Another approach to generating coherent radiation is the free electron laser (FEL) [29]. The operation of FEL's in the infrared is now a well established technology. The requirements on the electron accelerator driving the FEL become more difficult as the radiation wavelength is reduced. The development of FEL's in the ultraviolet is a very exciting possibility. The shortest wavelength FEL thus far achieved is the optical klystron [30] installed on the VEPP-3 storage ring in Novosibirsk, which has lased from 2400-6900Å. Storage rings are very attractive as FEL drivers [31], since they offer high brightness electron beams and very stable operation. They may offer the best path to the development of high average power devices. On the other hand, the recent development of laser driven photocathode electron guns [32] has lead to the achievement of very high brightness electron beams from linear accelerators. The photoinjector for the Los Alamos High Brightness Accelerator Facility [33] has produced a 17 MeV electron beam with a peak current of 300 Amp, 0.3% energy spread and normalized rms emittance $\epsilon_n = \gamma\epsilon = 8$ mm-mrad. Extrapolating this performance to a few hundred MeV, this exceeds the brightness one can expect to achieve in a storage ring, whose performance is limited by the microwave instability and intra-bunch scattering. Therefore, linac driven FEL's are very attractive possibilities in the ultraviolet, and may provide the best path to the highest peak power. An innovative design of an XUV FEL oscillator based upon a room temperature linac and a ring optical resonator has been presented by a group at Los Alamos [34]. A different approach utilizing a subharmonically seeded single pass FEL amplifier driven by a superconducting linac has been proposed by a group at Brookhaven [35]. The achievement of peak powers of a few hundred megawatts below 1000Å now appears feasible.

VIII. POLARIZATION

The utilization of the polarization of synchrotron radiation is increasing, and the development of new types of polarized insertion devices [36] is opening up new experimental opportunities. Bending magnet radiation is linearly polarized in the midplane, and elliptically polarized off the midplane. Radiation from a planar wiggler or undulator is linearly polarized everywhere. The linear polarization arises from the antisymmetry of the electron trajectory in a period. Goulin, Elleaume and Rauox [37] have proposed an asymmetric wiggler, in which poles of opposite polarity have unequal peak field strength, but equal field integral. In this case elliptically polarized radiaton will be observed off the midplane.

Yamamoto and Kitamura [38] have developed an elliptical wiggler producing elliptically polarized radiation in the midplane. This device is comprised of a vertical periodic field with large strength parameter $K_y \geq 10$, and horizontal periodic field with small $K_x \approx 1$, shifted longitudinally by one-quarter period relative to the vertical field. The wiggler radiation in the midplane comes from a sequence of arc sources due to the strong vertical field. The horizontal field produces an alternating tilt, up and down, between adjacent poles. Hence the radiation in the forward direction comes from above and below the midplane of adjacent arc sources, cancelling the negative phase due to the opposite sign of the bending radius. Therefore, the out-of-phase component of the radiation adds rather than cancelling, and elliptically polarized radiation is produced.

Kim [39] has proposed a device comprised of a horizontal and vertical undulator separated by a dispersion section. This device produces a horizontally polarized wave following a vertically polarized wave by a time interval which can be rapidly modulated by varying the magnetic field in the dispersion section. A more conventional elliptically polarized wave results when the radiation pulse is lengthened in a monochromator to produce narrow spectral bandwidth.

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