ANL/XFD/CP-- 90440
CONF- 9604136--23

RECEIVED
JUL 18 1996
OSTI

Insertion Devices at the Advanced Photon Source

Elizabeth R. Moog

Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439

Abstract. The insertion devices being installed at the Advanced Photon Source cause the stored particle beam to wiggle, emitting x-rays with each wiggle. These x-rays combine to make an intense beam of radiation. Both wiggler and undulator types of insertion devices are being installed; the characteristics of the radiation produced by these two types of insertion devices are discussed, along with the reasons for those characteristics.

INTRODUCTION

When a charged particle is accelerated so that either its speed or trajectory is changed, it will emit radiation. The electrons or positrons in the Advanced Photon Source (APS) beam are accelerated when their trajectory is bent, as it is by the bending magnets that make the beam travel in a circle. The x-rays emitted at each of these bends go off in a direction tangential to the arc of the particle beam.

While bending magnets produce beams of x-rays that are useful to the users of the APS, much more intense beams of x-rays are produced by the insertion devices. In an insertion device, the particle beam is made to wiggle back and forth many times. The radiation from each wiggle is emitted in the same forward direction, so that all the radiation piles up into a very intense beam of x-rays.

The particle beam is made to wiggle by the magnetic field of the insertion device. As the particle moves through the insertion device, it encounters a magnetic field that is first up, then down, then up, then down, etc. This magnetic field is created by two arrays of permanent magnets alternating with pole pieces. A section of the magnetic structure is shown schematically in Fig. 1. The magnets are magnetized in a direction parallel to the particle beam. The magnetic flux produced by the magnets is then focused by the pole pieces across the gap between the two arrays. This gap is where the particle beam travels. The advantage of having pole pieces to direct the flux across the gap is that the poles even out non-uniformities in the magnets. The permanent magnets are made of neodymium-iron-boron and are very strong. Manufacturers of the Nd-Fe-B magnets can only make a set of magnets with the same strength to within about 2% (at least, for a reasonable price!). The magnetic fields of the insertion devices need to be more precise than that, however, so having the poles direct the flux allows a stronger magnet to be paired with a weaker one to produce an average net field.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

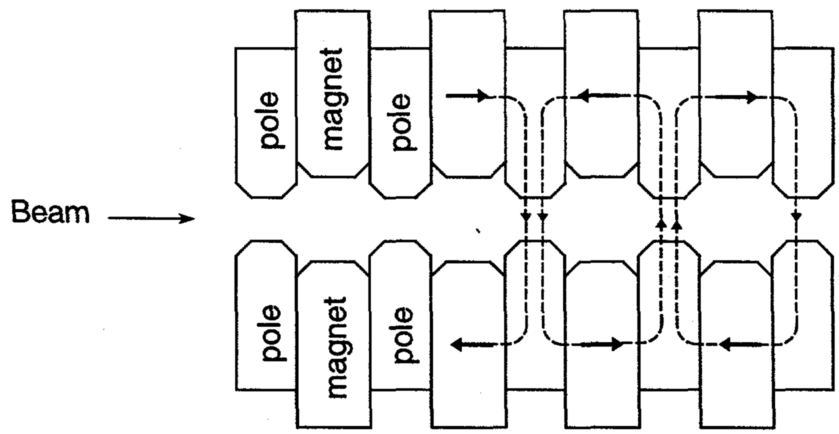

Figure 1. A schematic drawing of an insertion device magnetic structure. The magnetization direction of the magnets is shown by the arrows. The dotted lines show the magnetic flux in the poles and in the gap of the insertion device where the particle beam travels.

CHARACTERISTICS OF UNDULATOR RADIATION

Twenty-three different insertion devices are now either installed in the APS storage ring, awaiting installation, or under construction. These devices include: 17 standard Undulators A with a 3.3-cm period, 2 Wigglers A with an 8.5-cm period, one-of-a-kind undulators with period lengths of 2.7 cm, 5.5 cm, and 1.8 cm, and an elliptical wiggler. Most of the users of the APS preferred the general-purpose Undulator A, but a few wanted special devices.

The obvious question is: What is the difference between an undulator and a wiggler? To understand this, we need to know something about the characteristics of the light emitted by an undulator.

A first guess about what the spectrum of light from an insertion device would be is that it would be the same as for a trajectory with a single bend, but multiplied by the number of bends. That does indeed give an overall envelope for the spectrum, but other effects also significantly affect the spectrum.

Consider the trajectory of the particle in the insertion device, as shown schematically in Fig. 2a. (That figure is most definitely not drawn to scale -- the period of the trajectory wiggles is typically a few cm, while the amplitude of the wiggles is a few microns.) The biggest acceleration seen by the particle is at the peaks in the trajectory. As a particle rounds one peak, it emits a photon that travels off at the speed of light. The particle continues on with its wiggly trajectory, and when it gets to the next peak it emits another photon. The particle is traveling at very nearly the speed of light (at 7 GeV, its speed is 0.999999997 of the speed of light) but, because of its longer wiggly path, doesn't reach the next wiggle until after the photon has gone by. The second photon will then follow behind the first photon. To an observer downstream, the emitted light looks like a series of quick flashes of light, one from each wiggle. This time structure in the emitted light means that instead of having a smooth distribution of light over a wide frequency range, the spectrum has sharp intensity peaks at the characteristic frequency of the flashes of light and at its harmonics(1,2). A typical undulator spectrum is shown in Fig. 3. If the magnetic field of the undulator is very precisely periodic so that the time structure in the light pulses is very regular, then this harmonic structure can continue out to very high harmonics. However, errors in the periodicity (called phase errors) can result in marked loss in intensity at the high harmonics. The insertion devices at APS have been specifically tuned so that the spectrum of light they produce is very nearly what would be expected from an ideal undulator.

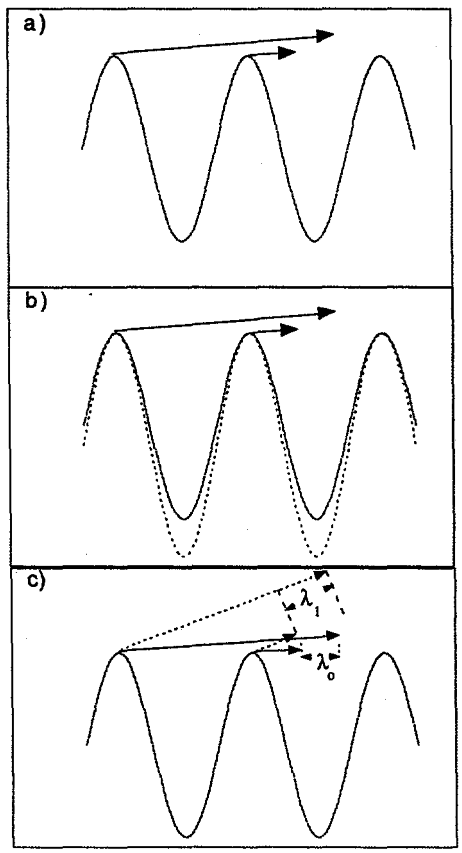

Figure 2. Schematics to illustrate the origin of the harmonic structure in an undulator spectrum. See text for explanation.

We can now ask what happens as the strength of the magnetic field from the insertion device is changed. Although the field is produced by constant-strength permanent magnets, the strength of the field in the gap where the particle beam travels can be increased by moving the upper and lower magnetic arrays closer together (while still leaving room for the vacuum chamber that carries the particle beam!). Figure 2b shows the trajectories of particles for two different strength magnetic fields. When the magnetic field is stronger, the particle goes through larger bends so that the amplitude of the trajectory wiggles is larger. The longer path length results in the particle being delayed even more in reaching the second emission point, so that the train of pulses seen by the observer is spaced out more -- i.e., the characteristic frequency shifts to a lower value. Indeed, what is seen is a shift in the energy of the first harmonic to lower values as the strength of the magnetic field is increased. This feature of undulator radiation means that the user can adjust the gap of the undulator to tune the radiation to the desired energy.

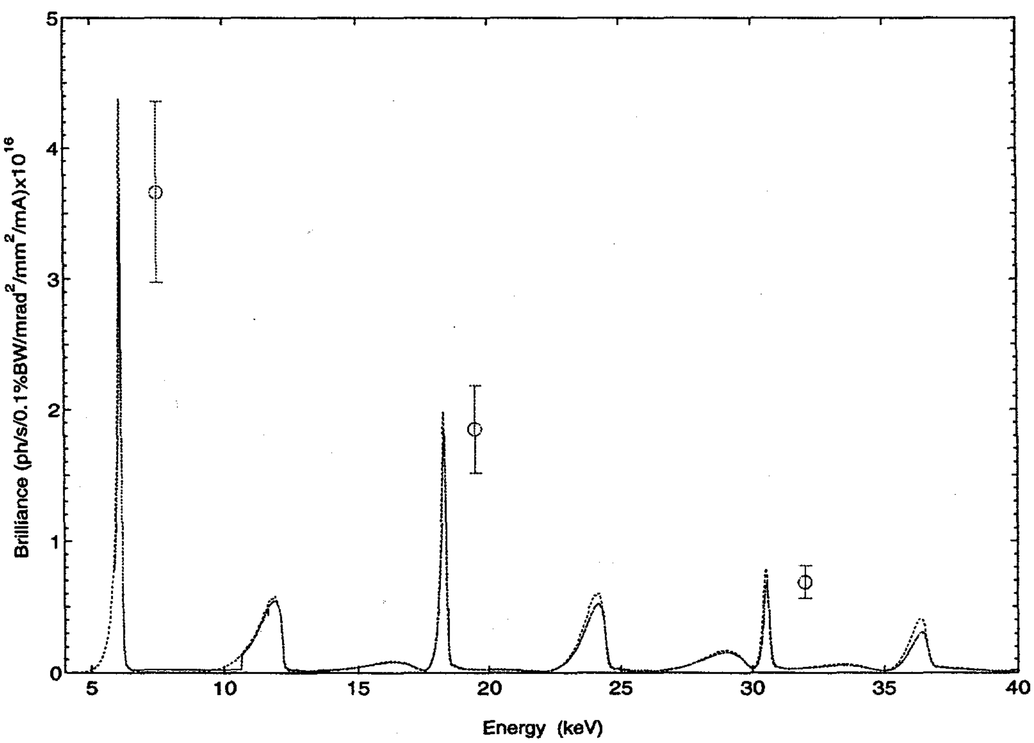

Figure 3. Spectrum of x-rays from an undulator, showing the pronounced harmonic structure. The solid line is the measured spectrum; the dotted line is the predicted spectrum. The peak near 6 keV is the first harmonic.

Another interesting question to ask is what happens to the light from an undulator if it is viewed from a position that is slightly off-axis. This condition is shown schematically in Fig. 2c. For the light that is viewed from an angle, the particle spends relatively less of its time traveling in the same direction as the light. As a result, the first photon gets more of a head start over the second photon (as in the figure, the wavelength λ_1 is longer than λ_0), so that the characteristic frequency of the train of pulses shifts to a lower value. This is seen as a red shift in the light as the observation point is moved off-axis.

CHARACTERISTICS OF WIGGLER RADIATION

With a wiggler, the effects described above for an undulator still occur, but with differences. The magnetic field of a wiggler is much stronger than that of an undulator, for the same period length. Therefore, the first harmonic of the emitted radiation occurs at a much lower energy. In fact, it winds up being much lower in energy than where most of the flux is. (Remember that the spectrum from a single bend gives an overall envelope for the radiation spectrum.) At the energies where the flux is largest, the harmonics are very close together. If everything were perfect, the wiggler spectrum would show this harmonic structure. However, real-life effects serve to smooth it out. First, the optics of a beamline accept a finite rather than infinitesimal width in energy, so some energy averaging occurs. Second, the beamline optics accept the radiation that comes through a small but finite-sized pinhole. Some of the radiation coming through the pinhole is apt to be from a higher harmonic but slightly off-axis so that it has red-shifted down to the energy range of interest. Third, a real beam doesn't consist of just one particle, but of a large number of particles with some variation in position, trajectory, and energy. These variations result in smoothing of the harmonic structure. Finally, the field of the insertion device may be carefully tuned, but it isn't perfect. All of these effects serve to smear out the harmonic structure of the wiggler beam. The net effect is that the wiggler spectrum can be considered for all practical purposes to be the same as the spectrum from a single bend in the trajectory, but multiplied by the number of wiggles.

ACKNOWLEDGMENTS

The author wishes to thank R. Dejus for discussions of undulator radiation characteristics and R. Dejus, P. Ilinski, and Z. Cai for the graph of the undulator spectrum. This work was supported by the U.S. D.O.E. under contract #W-31-109-ENG-38.

REFERENCES

1. For the formal mathematics describing the characteristics of the undulator spectrum, see Kim, K.-J., *Physics of Particle Accelerators*, AIP Conference Proceedings 184, New York: American Institute of Physics, 1989, pp. 565-632.
2. In this explanation of the origin of the undulator spectrum, the pulses of radiation from the bottom wiggles in the picture have been neglected. Those wiggles will also produce radiation pulses, but the electric vector of the electromagnetic wave is opposite in direction to that of the pulses from the top wiggles. The characteristic frequency therefore is from the full period of the undulator, as described, and the effect of the bottom wiggles is to markedly decrease the strength of the even harmonics of the radiation (at least for strictly on-axis radiation).