NOVEL INSERTION DEVICES*

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Abstract

Permanent magnet planar undulators are used at synchrotrons worldwide and serve as versatile radiation sources. For some experiments, however, photon characteristics other than what is achievable with planar devices are desired. Undulators can be tailored to adjust photon characteristics, such as brightness, tuning curves, polarization, harmonic content, and heat load, to suit them to a particular experiment. One specialized device is the electromagnetic circularly polarizing undulator at the Advanced Photon Source (APS). At a few facilities, plans are underway to build superconducting undulators with short period lengths to provide higher energy radiation. At APS, the possibility of building an undulator with a variable period is also being investigated. Some users, driven by a desire for lower on-axis heat load or for circular polarization, prefer other types of devices, such as Apple-style undulators or figure-eight devices. Characteristics of the radiation output and advantages of these various types of devices are presented.

INTRODUCTION

The designers of synchrotron radiation facility beamlines have choices to make in their selection of an insertion device (ID) for the beamline. The overall length of the device is typically a predetermined standard length based on the space available, and the minimum gap is determined by storage ring considerations and the vacuum chamber size (or, if there is no vacuum chamber in the ID gap, by the effect on beam lifetime [1]), but the period length and magnetic configuration (i.e., planar, helical, or other) can be selected. These will determine the polarization characteristics, tuning range, and power output.

PLANAR UNDULATORS

A sample set of tuning curves intended to guide a user in selecting the period length for a new planar device is shown in Fig. 1. The user expects to concentrate on energies near the Se and Br edges, but does not want to sacrifice tunability. For each of the period lengths shown, the number of periods has been changed to keep the overall device length constant at 2.1 m. As can be seen, the on-axis brilliance would be higher for the shorter period length undulators, but if the period length gets too short there will be a gap between the 1st and 3rd harmonics. Extending the 3rd harmonic to lower energy so it would overlap the 1st would require higher magnetic field strength than can be readily achieved by a planar undulator at the 10.5-mm minimum gap allowed by the standard APS ID vacuum chamber.

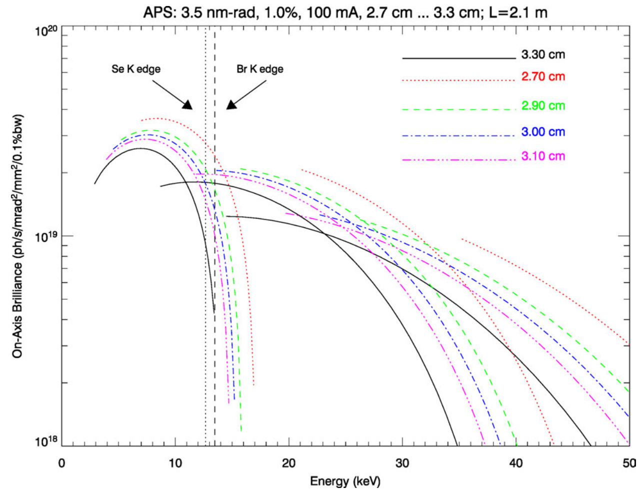

Figure 1: Tuning curves of on-axis brilliance vs. photon energy, showing the 1st, 3rd, and 5th harmonics for different period length undulators. Number of periods is adjusted to keep the overall undulator length constant at 2.1 m. A shorter period length gives higher brilliance but may result in a gap between harmonics.

Another important consideration for the user is the power output of the ID – either total power, power density or both. Figure 2 shows the total power and the ratio of the brilliance to the total power as a function of photon energy. (The trends for the power density look very similar.) The highest power comes at small gap, whether the energy to be selected is the 1st, 3rd, or 5th harmonic. There are differences in the details of the power load between the different period lengths, but clearly the biggest difference in power is determined by whether the desired energy can be reached in the 1st harmonic rather than requiring the 3rd and a closed gap.

In-Vacuum Undulator

The peak magnetic field can be increased by decreasing the gap. To overcome the limit imposed by the vacuum chamber, the entire undulator can be put in vacuum [1-3]. Shorter period lengths become reasonable because the device can be taken to magnetic gaps that are a few mm smaller – the limit comes when the beam lifetime begins to be affected. Additional precautions must be taken to ensure that the magnets and poles are vacuum-compatible and bakeable. The magnetic arrays must present a smooth conductive face to the beam so as to avoid resistive-wall instabilities; this can be accomplished with a Cu/Ni foil laid over the magnets. The Cu conductive face is toward the beam and the Ni is attracted to the magnets and holds the foil in place. The magnets will be closer to the beam where they are exposed to higher radiation levels, so radiation-induced demagnetization is a greater hazard and due consideration should be given to the choice of magnet material.

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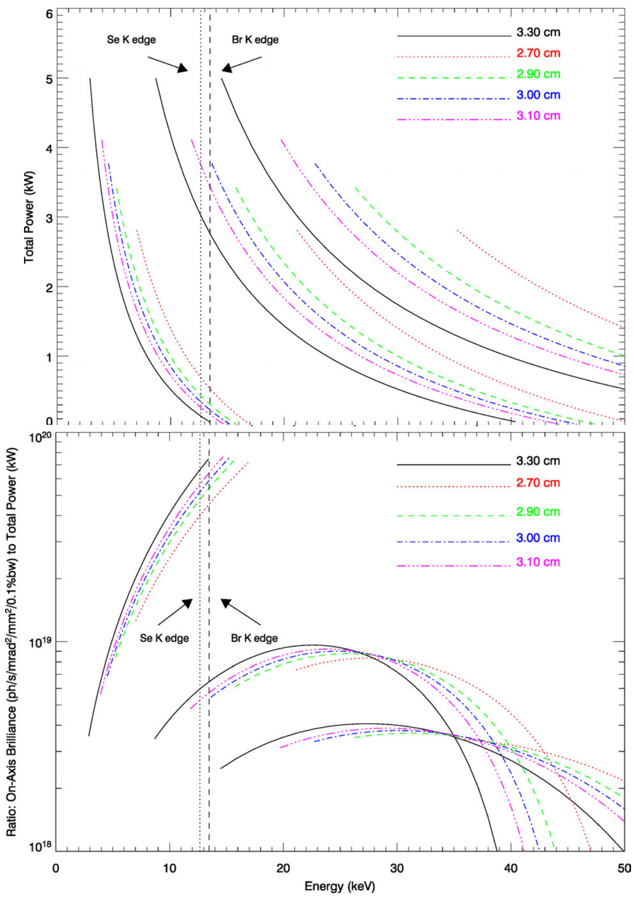

Figure 2: Total power (top) and brilliance/power (bottom) vs. energy for the same undulators as in Fig. 1. There are differences in the power levels for the different period lengths, but the most significant minimization in power (and maximizing of ratio) is when the desired energy can be reached in the first harmonic rather than the third.

Superconducting Undulator

Superconducting undulators have been proposed as a means of going beyond the field strengths that are achievable with in-vacuum undulators. Although superconducting wavelength shifters and wigglers have been built and used [3], meeting the magnetic field quality requirements of undulators has been a challenge. Recently, a test section of undulator was built [4]. A similar scheme that is under consideration at APS is shown in Fig. 3. An Fe mandrel has slots cut into it where the superconducting wire is wound. The Fe material between the slots acts as poles, and there are two mandrels, one above and one below the beam axis. Challenges anticipated in making such a device work include providing sufficient cooling such that beam heating effects do not cause quenching, and developing the techniques needed to measure the magnetic field and to attain the necessary field quality.

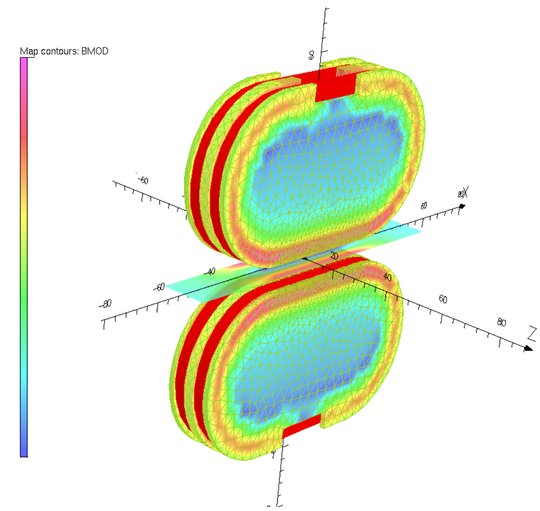

Figure 3: Model for a superconducting undulator. Slots for the superconductor windings are cut into the iron mandrels, one above the beam and the other below. The remaining part of the mandrel serves as pole pieces. Also shown is the result of a calculation of |B|.

Variable-Period Undulator

A variable-period undulator based on a staggered array undulator [5] has been proposed [6]. As with a staggered array, a solenoid with a strong axial field has vanadium permendur poles inserted in the bore, as shown in Fig. 4. The poles perturb the field as shown in Fig. 5, resulting in a periodic transverse or vertical field on axis. To make the period vary, the poles can be moved in position longitudinally. Although the magnetic field on axis of such a device is weaker than for a permanent-magnet undulator of the same period length and gap, the tunability range can still be quite wide. In addition, the period chosen to reach a particular energy photon can be the period where the peak in the tuning curve falls at that energy, making for a higher brilliance, as shown in Fig. 6. A further advantage of this type of device is that the high brilliance does not come with the penalty of a high power output. Instead, as shown in the lower panel of Fig. 6, the power remains low compared to a standard planar undulator.

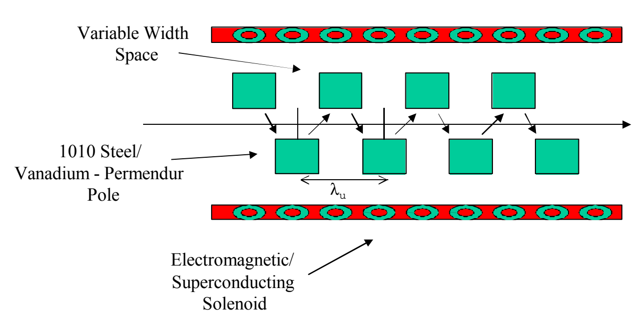

Figure 4: Schematic for a variable-period undulator.

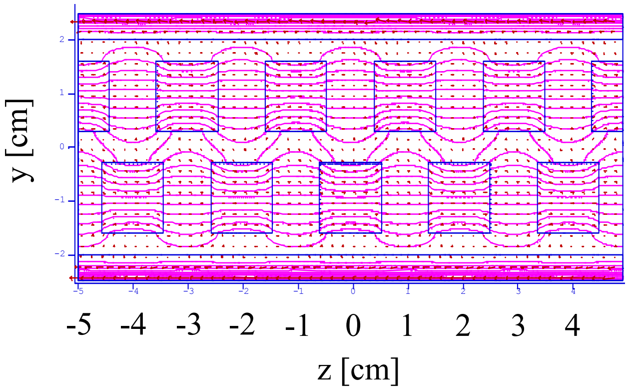

Figure 5: Magnetic flux lines show the effect of the steel poles on the solenoid field. A spatially oscillating undulator field results on axis.

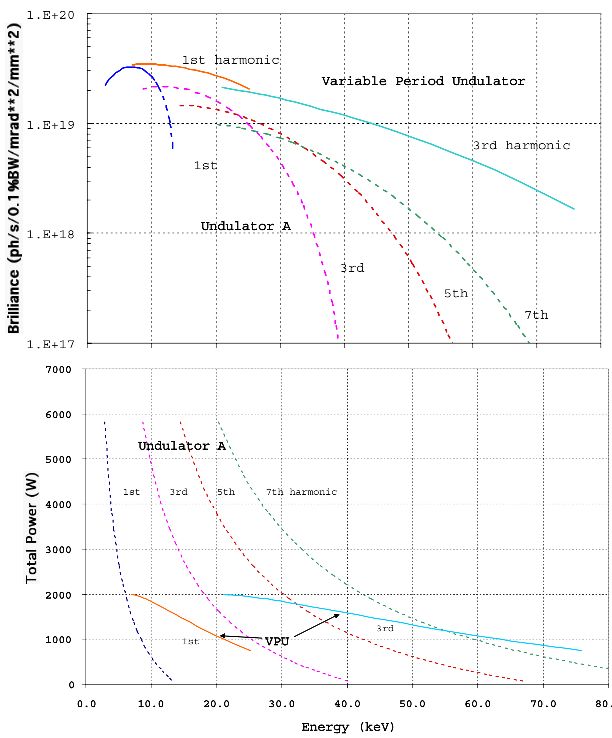

Figure 6: Brilliance and total power from a variable-period undulator, as compared to a standard APS planar Undulator A. The brilliance matches or exceeds that of Undulator A, while the power load is much lower.

VARIABLE POLARIZATION DEVICES

The radiation of a standard planar undulator is linearly polarized in the wiggle plane (usually horizontal). Some experiments, however, need circularly or elliptically polarized light, and some of those experiments are helped significantly if the polarization can be switched rapidly between left- and right-handed circular polarization.

Wigglers

Segments of the trajectory of the beam through the undulator, taken alone, will produce circular polarization–consider the lobe of the trajectory where the acceleration is constant in direction. If viewed from above or below the plane of the beam wiggles, that trajectory segment is a half circle and will produce circularly polarized light if its radiation can be separated from the radiation from the return lobe of trajectory. One scheme to accomplish this separation is the asymmetric wiggler [7], in which there is a strong field in one direction over a short distance followed by a weaker field over a longer distance. (The field integral still must be zero to avoid perturbing the beam in the rest of the storage ring.) Radiation from the weaker field is less intense and at a different energy than that from the strong field, so the net effect is quasicircular polarized radiation with one handedness above the wiggle plane and the other below.

Another scheme is an elliptical wiggler [8], where, instead of viewing the light from an off-axis angle, the beam trajectory is tilted up for one lobe and down for the other. This is accomplished by a magnetic field with a strong oscillating vertical field component and a weak oscillating horizontal field component that is shifted by a quarter period with respect to the vertical field. The elliptical trajectory gives circularly polarized light on axis and bright linearly polarized light above and below the axis. If the weaker horizontal magnetic field is provided by an electromagnet with a switchable power supply, the handedness of the circular polarization can be switched.

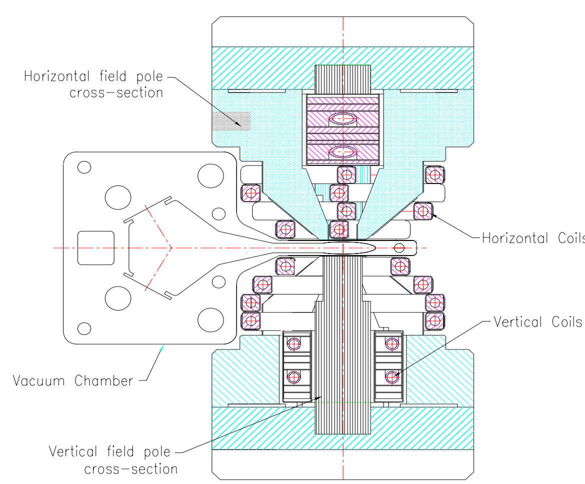

Figure 7: Cross section of an all-electromagnetic circular polarizing undulator. The top shows a cross section through horizontal-field poles, the bottom through a vertical field pole. The vertical poles are offset from the horizontal ones by a quarter period so the particle trajectory can be circular if the vertical and horizontal field strengths are equal. Depending on which coils are carrying current and the amount of current, the polarization can be circular, vertically linear, horizontally linear, or elliptical.

Undulators with a Variety of Polarizations

Switchable circular polarization can also be obtained from an undulator, and these undulators can be very flexible devices that allow a variety of different polarizations. An all-electromagnetic device in use at APS [9] is shown in Fig. 7. This undulator can deliver either-handedness of circular polarization and switch between them at up to 10 Hz. If only the vertical (or horizontal) field coils are powered, it will deliver horizontally (or vertically) linearly polarized light. Elliptical polarization is possible if both the vertical and horizontal fields are on, but delivering different field strengths.

This all-electromagnetic circularly polarizing undulator has a relatively long period of 12.8 cm and delivers light in the 0.5- to 3-keV range. To deliver higher energy light, the period length would have to be made shorter. A significantly shorter period is not feasible for a conventional electromagnetic device, however, because there would be no room for the coils. Instead, if a shorter period length is desired, a permanent magnet "Apple-style" undulator can be used.

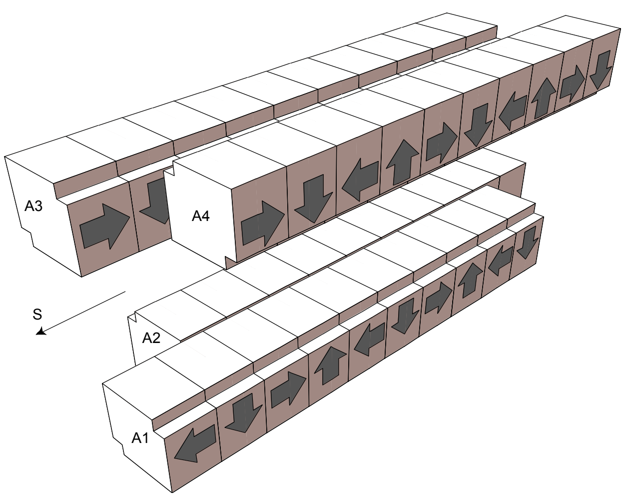

Figure 8: Apple-style undulator. Two arrays of magnets above the beam axis and two arrays below the beam create the undulator field. They can be shifted longitudinally with respect to one another in order to vary the polarization.

An Apple undulator [10], shown in Fig. 8, has four separate magnetic arrays, two above the beam and two below. In addition to opening and closing the gap to adjust the field strength, the arrays can be shifted lengthwise with respect to one another. Depending on the phase between the arrays, it can produce either vertical or horizontal linear polarization, either left- or right-handed circular polarization, or elliptical polarization. Switching between the different polarizations is possible, but involves a mechanical motion and so is not as fast as for the electromagnetic devices.

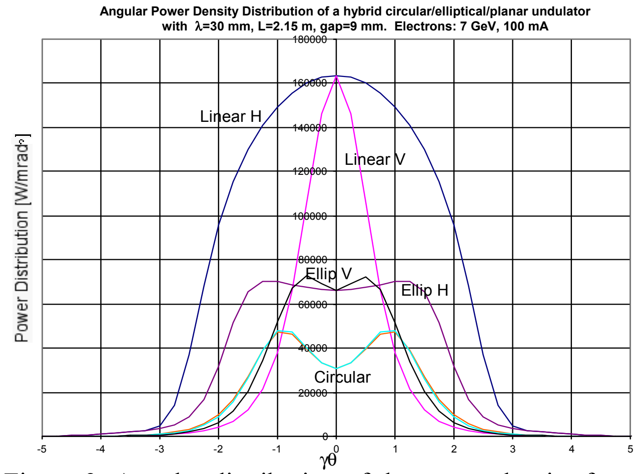

Figure 9: Angular distribution of the power density from an Apple-style undulator in different polarization modes. On-axis power density is lowest with circular polarization.

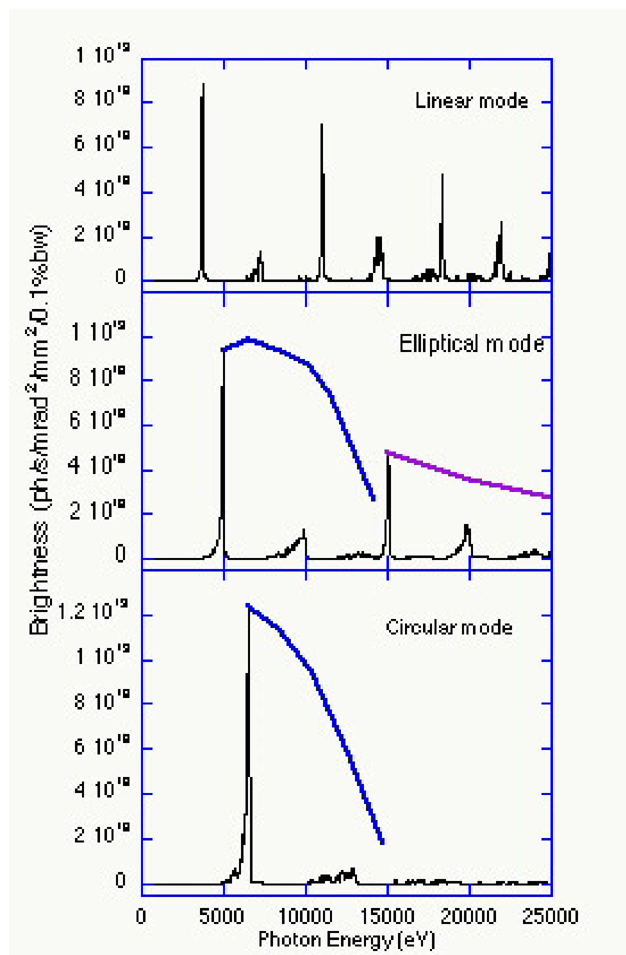

Figure 10: Brightness from an Apple-style undulator in various polarization modes. The brightness in the circular mode is high despite the reduced power.

Circular polarization that results from a helical trajectory of the particle beam has the advantage that there are no higher harmonics of the radiation on axis. This reduces the problem of high-harmonic contamination. Another advantage comes in the spatial distribution of the power. Figure 9 shows the angular distribution of the power density from an Apple undulator in linear, circular, and elliptical polarization modes. The on-axis power is lowest in the circular mode, and the power continuing down the beamline can be reduced further with a mask that stops the ring of radiation at the angle $1/\gamma$. The lower power in circular polarization mode does not come at the cost of reduced useful brightness, though, as can be seen in Fig. 10. In circular mode the brightness is even higher than in the linear mode.

There are challenges involved with an Apple-style undulator, however. While the magnetic field of a planar undulator is very uniform through some transverse distance, the Apple magnetic field clearly is not. This results in beam focusing effects that are intrinsic to the device and that vary with gap and phase. Various schemes have been developed to correct the devices, but they don't work for all phases. As a result, much of the compensation for the device's effect on the beam orbit and tune has to be external to the device.

Figure-8 Undulators

The conventional way of producing lower-energy photons for a user is to increase the period length of the planar undulator. Particularly with the higher-energy, 6- to 8-GeV storage rings, this reaches the point where the power levels in the photon beam become excessive. Figure-8 undulators provide an alternative [2]. The magnetic array shown in Fig. 11 has an array of magnets at the center of each jaw to produce a vertical field with one period. Side magnet arrays produce a horizontal magnetic field with a period length that is twice as long. Viewed from the end, the particle beam trajectory will be a figure eight. As with a circular polarizing undulator, the particle trajectory never points directly down the nominal beam axis, so neither does most of the power. Instead, the distribution of the power resembles a < sign, as shown in Fig. 12. A mask or pinhole can block the intense power and allow only the on-axis radiation through. Although the power level is reduced compared to a conventional undulator, the flux in the fundamental harmonic remains as high as for the conventional undulator. The figure-8 undulator also produces half-integer harmonics in the radiation spectrum due to the longer period side magnet arrays. The linear polarization of the radiation can be vertical or horizontal, depending on whether it is an integer or half-integer harmonic.

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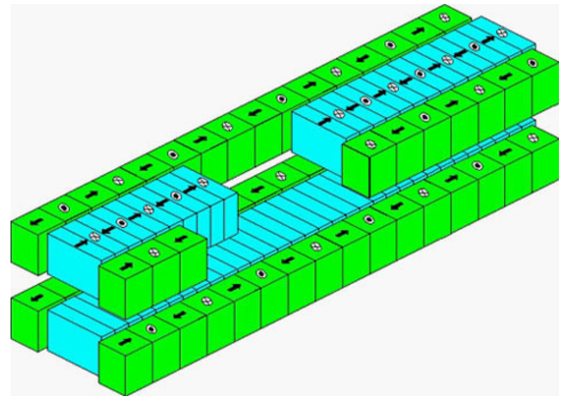

Figure 11: Magnetic structures of a figure-8 undulator. The side arrays produce a horizontal magnetic field with a period twice as long as that of the vertical field.

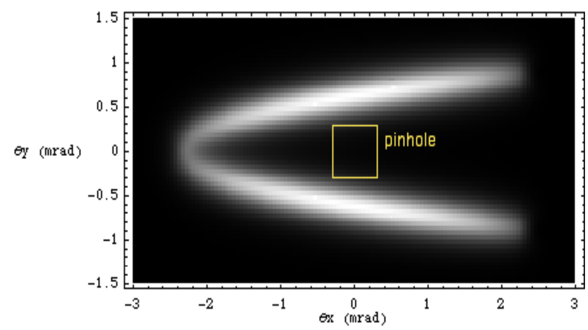

Figure 12: Spatial power distribution from a figure-8 undulator. The pinhole shown will block most of the power but still transmit as much first-harmonic flux as a conventional undulator.

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