Handbook of X-ray Imaging
Physics and Technology
Paolo Russo

X-ray Shutters

Publication details
Naresh Gandhi Kujala
Published online on: 14 Dec 2017

Accessed on: 05 Dec 2023
9

X-ray Shutters

Naresh Gandhi Kujala

CONTENTS
9.1 Introduction .................................................................................................................. 175
9.2 Different Types of X-ray Sources .................................................................................. 176
9.3 X-ray Shutter Design .................................................................................................... 176
9.4 Applications of X-ray Shutters ..................................................................................... 179
9.5 Commercially Available X-ray Shutters ...................................................................... 180
9.6 Summary and Conclusion ............................................................................................ 182
Acknowledgments .................................................................................................................. 182
References .............................................................................................................................. 182

9.1 Introduction

The term “shutter” implies the deliberate introduction of material between the radiation source and an object to reduce the radiation intensity and, hence, damage to the object. However, attenuation and absorption of radiation are also important in radiotherapy and radiation processing, where the aim is to deliver a precise amount of radiation “dose” to a tumor or sample. It is easy to shield ion and electron sources; almost any material thicker may be used to stop all ions. Electrons are easily stopped by a few millimeters of any solid material.

X-rays are produced when accelerated electrons collide with solid matter. When X-rays interact with any form of matter, they are partly transmitted and partly absorbed. Their kinetic energy is transformed to bremsstrahlung radiation. Bremsstrahlung radiation has a broad spectrum of range of X-ray wavelengths. More details of X-rays production can be found in Chapter 2 and Chapter 10 of this book. Any bremsstrahlung generated can be attenuated by materials like lead, tungsten, and so on.

In order to access the beamlines, sample chambers, and experiment hutch (end stations) while the X-ray machine is in operation, the radiation has to be blocked, allowing users to work without switching off the source. The number of X-rays passing through materials depends not only on the material thickness and density, but also on the absorption properties for the energy needed to be absorbed. As described in Section 1.1, the absorption coefficient depends on the atomic number (Z) for a given wavelength, so a higher Z value would be a better X-ray shutter. For this reason, molybdenum, lead, and tungsten are commonly used for the fabrication of X-ray shutters. When a shutter blocks X-rays, the photon energy is converted to heat that needs to be dissipated by cooling it. In addition, heat generated by absorption of radiation or transmitted from the source can induce thermal stresses.

For synchrotron sources, absorbing the undulator and bremsstrahlung beam by photon shutter is integrated with a personal safety interlock (Moini et al. 1989). The dose rate from the insertion device (undulator source) can be calculated by the equation (Frank 1988):

\[ D = \frac{f N_0 \pi \alpha^2 X_0 L (L + l)}{h \gamma}, \]  

(9.1)

where \( D \) = total dose rate in Sv/h; \( f \) = effective flux-to-dose conversion factor; \( \alpha = 1/\gamma \), the ratio of positron rest mass to its kinetic energy; \( N \) = number of positrons/second for the beam current; \( X_0 \) = radiation length of air in centimeters; \( L \) = effective length of the straight section in centimeters; and \( l \) = distance from the end of the straight section in centimeters (at the point of observation).

The X-ray photon shutters are placed at the entrance of the experiment station for most of the laboratory X-ray sources. Typically, for synchrotron sources, the first optical enclosure (FOE) on synchrotron beamlines has an X-ray photon shutter that is used to protect the front-end optical components. Usually, there are three different types of X-ray beams defined: (1) white beam; (2) pink beam; and (3) monochromatic beam. There are X-ray photon shutters immediately downstream from the monochromator to pass either the mono beam or the white-beam to the experiment station. The design of the photon shutter is integrated with a white-beam photon stop, a safety stop, and a collimator. The white-beam consists of the high-power X-rays and the bremsstrahlung radiation. The white-beam photon stop is designed to absorb the high-power X-rays. The safety stop and collimator are designed to block the bremsstrahlung radiation. One has to design X-ray shutters depending on the position of shutter in the beamline.

Conventional X-ray beam shutters for synchrotron X-ray diffraction topography use rather low shutter speeds, with a
minimum exposure time of approximately 1 second. Since some single crystals have a very strong reflection capability, there are real-time applications that would benefit from very short exposure times. Therefore, a high-speed shutter with a speed range from 1/100 second to a few seconds is very useful in synchrotron topographic experiments.

In this chapter, a detailed description of X-ray shutters is given, although it is not intended to enter into an elaborate account of the finer points of details involved in the many different makes and designs of shutters available. For such a description, the readers must refer to the more specialized text books and literature papers; here we present the different types of X-ray shutters design that have already been implemented and are working at different facilities.

### 9.2 Different Types of X-ray Sources

Laboratory X-ray sources that operate with a tube voltage in the range of 5 to 60 kV and a tube current in the range of 0 to 20 mA can be classified into two types: (1) X-ray tube sources (sealed tubes), and (2) rotating anode X-ray generator sources. There are higher energy sources, like synchrotron sources with an electron energy range of 2 to 8 GeV, and X-ray free electron laser (FEL) sources with an electron energy range of 8 to 17 GeV (see Section I, Chapter 8 of this book).

There are several commercial companies that sell the X-ray tube sources and rotating anode X-ray sources, such as Oxford Instruments (www.oxford-instruments.com), Newton Scientific (www.newtonscientificinc.com), Amptek, Inc. (amptek.com), Varian Medical Systems (www.varian.com), and Rigaku Corporation (www.rigaku.com). Table 9.1 shows the different types of anode materials used for X-ray tubes and rotating anode X-ray generators (see Section I, Chapters 2 and 3 of this book). The applications of X-ray tube sources for radiological medical imaging are explained in detail in Section II (“X-ray Radiography”) of this book.

The design of X-ray tube housing should be constructed in such a way that, with all shutters closed, the radiation measured at a distance of 5 cm from its surface is not capable of producing a dose in excess of 2.5 millirems in 1 hour. For systems utilizing X-ray tubes, this limit should be met at any specified tube rating. The engineering design of X-ray shutters are described by the (1) source strength, spectrum, angular distribution, spatial distribution, and time dependence for each type of radiation; and (2) maximum allowable dose and heating.

Almost every design and engineering of X-ray photon shutters is unique, each designed just well enough to stop photons of a particular source in the available space along the beamline at a fast-enough speed. For X-ray tubes and rotating anodes, a thick block of tungsten should do the job by inserting into the beam path, which should absorb almost all the photon flux and allow users to work safely at the sample chamber without turning off the source. The shutters are driven with a solenoid or pneumatic

### Table 9.1

<table>
<thead>
<tr>
<th>Target Material</th>
<th>Atomic Number</th>
<th>(K\alpha) Wavelength (Å)</th>
<th>(K\alpha) Energy (keV)</th>
<th>(K\beta) Wavelength (Å)</th>
<th>(K\beta) Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium (Cr)</td>
<td>24</td>
<td>2.29</td>
<td>5.42</td>
<td>2.08</td>
<td>5.94</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>26</td>
<td>1.94</td>
<td>6.41</td>
<td>1.76</td>
<td>7.07</td>
</tr>
<tr>
<td>Cobalt (Co)</td>
<td>27</td>
<td>1.79</td>
<td>6.94</td>
<td>1.62</td>
<td>7.65</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>28</td>
<td>1.66</td>
<td>7.48</td>
<td>1.50</td>
<td>8.24</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>29</td>
<td>1.54</td>
<td>8.01</td>
<td>1.39</td>
<td>8.92</td>
</tr>
<tr>
<td>Molybdenum (Mo)</td>
<td>42</td>
<td>0.709</td>
<td>17.5</td>
<td>0.632</td>
<td>19.6</td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>47</td>
<td>0.559</td>
<td>22.2</td>
<td>0.497</td>
<td>25.2</td>
</tr>
<tr>
<td>Tungsten(^a)</td>
<td>74</td>
<td>1.48 ((L\alpha))</td>
<td>8.40</td>
<td>1.28 ((L\beta))</td>
<td>9.67</td>
</tr>
<tr>
<td>Gold(^b)</td>
<td>79</td>
<td>1.278 ((L\alpha))</td>
<td>9.7</td>
<td>1.084 ((L\beta))</td>
<td>11.43</td>
</tr>
</tbody>
</table>

\(^a\) Tungsten and gold are in the \(L\alpha\) and \(L\beta\) emission spectrums.
A safety photon shutter is a remotely actuated device that prevents a photon beam from traveling down a beamline into an experiment station. When the shutter is closed, two shielding blocks are positionned to stop bremsstrahlung and the white-beam, although either will completely block the beam in isolation if designed to provide adequate shielding. Also, the personnel safety interlock system (PSS) detects any shutter failure through redundant switches, and takes appropriate measures to shut off the beam during a fault condition. All shutters are designed in the “fail-safe” mode such that, in the event of a power, communication, or mechanical system failure, the shutter will come to a closed state and will remain in the closed state.

Here, we discuss the shutter designs that are already installed and working at some of the synchrotron facilities, such as the Advanced Photon Source (APS) in Chicago, IL, PETRA III at Deutsches Elektronen-Synchrotron (DESY) in Hamburg Germany, and Swiss Light Source (SLS) at Paul Scherrer Institute (PSI) in Villingen, Switzerland. At the synchrotron source, the X-ray beam is produced by bending magnet, insertion device, canted undulator, and wiggler device. X-ray shutters are one of the critical components on the front-end of the photon beamlines at the synchrotron light sources. For bending magnet sources, a piece of water-cooled copper (Cu) backed by a piece of tungsten (W) struck at 90° incidence works nicely as a beam stop, can be moved automatically in and out of the beam, and can be controlled by a pneumatic cylinder or a solenoid valve using a control system.

At the APS synchrotron facility, photon shutters are designed for a dose rate of 2.5 µSv/h (0.25 mrem/h) at 30 cm from the downstream side of the shutter (Nian et al. 1992a). However, for an incident beam of bremsstrahlung photons, it is assumed that half of the dose may be due to photoneutrons. Therefore, the design criteria adopted for the shutters was a photon dose rate of 1.25 µSv/h (0.125 mrem/h) at 30 cm from the downstream surface of the shutter.

### TABLE 9.2

<table>
<thead>
<tr>
<th>X-ray Resources</th>
<th>Parameter Calculations</th>
<th>Website</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 The Center for X-ray Optics (CXRO)</td>
<td>X-ray attenuation length, X-ray transmission, and so on</td>
<td><a href="http://henke.lbl.gov/optical_constants">http://henke.lbl.gov/optical_constants</a></td>
</tr>
<tr>
<td>4 X-ray oriented program (XOP)</td>
<td>Synchrotron source spectra, transmission characteristic of optical components, and so on</td>
<td><a href="http://www.esrf.eu/Instrumentation/software/data-analysis/xop2.4">http://www.esrf.eu/Instrumentation/software/data-analysis/xop2.4</a></td>
</tr>
</tbody>
</table>

Actuator to move in and out of the beam path completely. To determine the best material to use for the photon shutter, one must consider the material’s properties when subjected to a temperature gradient.

A safety photon shutter is a remotely actuated device that prevents a photon beam from traveling down a beamline into an experiment station. When the shutter is closed, two shielding blocks are positionned to stop bremsstrahlung and the white-beam, although either will completely block the beam in isolation if designed to provide adequate shielding. Also, the personnel safety interlock system (PSS) detects any shutter failure through redundant switches, and takes appropriate measures to shut off the beam during a fault condition. All shutters are designed in the “fail-safe” mode such that, in the event of a power, communication, or mechanical system failure, the shutter will come to a closed state and will remain in the closed state.

Here, we discuss the shutter designs that are already installed and working at some of the synchrotron facilities, such as the Advanced Photon Source (APS) in Chicago, IL, PETRA III at Deutsches Elektronen-Synchrotron (DESY) in Hamburg Germany, and Swiss Light Source (SLS) at Paul Scherrer Institute (PSI) in Villingen, Switzerland. At the synchrotron source, the X-ray beam is produced by bending magnet, insertion device, canted undulator, and wiggler device. X-ray shutters are one of the critical components on the front-end of the photon beamlines at the synchrotron light sources. For bending magnet sources, a piece of water-cooled copper (Cu) backed by a piece of tungsten (W) struck at 90° incidence works nicely as a beam stop, can be moved automatically in and out of the beam, and can be controlled by a pneumatic cylinder or a solenoid valve using a control system.

At the APS synchrotron facility, photon shutters are designed for a dose rate of 2.5 µSv/h (0.25 mrem/h) at 30 cm from the downstream side of the shutter (Nian et al. 1992a). However, for an incident beam of bremsstrahlung photons, it is assumed that half of the dose may be due to photoneutrons. Therefore, the design criteria adopted for the shutters was a photon dose rate of 1.25 µSv/h (0.125 mrem/h) at 30 cm from the downstream surface of the shutter.
At APS, Undulator-A with a length of 2.5 m for 100 mA produced a total power of 5.2 kW; at a distance of 18.13 m, the photon shutter receives a heat flux of 500 W/mm² at normal incidence. To withstand this power and power density from the source, the temperature distribution has been shown using the analytical solution with Gaussian heat flux. The material used is GlidCop. The thermal conductivity is 3.65 W/cm·°C. The photon shutter is set at an angle of 1.5° to the beam path. More detailed information for design and thermal analysis can be found in the references (Shu et al. 1992; Job and Micklich 2005; Nian et al. 1992b, 1994; Chang et al. 1995). Canted undulators at the APS synchrotron facility will produce the two beams in order to have two beamlines available for different applications. The details of design and analysis of photon shutters are explained in Jaski et al. (2002). The front-end has two fixed masks and two photon shutters (PS1 and PS2). Under closed-gap conditions, with a beam current of 200 mA, the total power will be 20.4 kW, with a peak power density of 281 W/mm² at the normal incidence.

In order to overcome such high power, a dog-bone shaped cross-section design has been developed for the photon shutter; the design drawing can be seen in Figure 9.2. Here, we highlight some of the designed parameters. Due to the high heat load on the photon shutters, large temperature gradients and thermal stresses are evident. The shutters are fabricated by brazing the top and bottom halves together. The top half is made of oxygen-free high thermal conductivity (OFHC) copper with a thick GlidCop face-plate brazed on it, with the bottom half made of OFHC copper. The properties of GlidCop are shown in Table 9.3. The shutters have water-cooling channels to efficiently dissipate rejected heat into the cooling water and, thus, minimize the thermally induced stress in them. The temperature and stress results of photon shutters implemented for canted undulators are shown in Table 9.4.

XOP is widely used for undulators and bending magnet sources power and power density calculations, but there are other codes developed by M. Meron at APS from CARS-CAT SRUFF (Meron, unpublished) that are written and run in Interactive Data Language (IDL).

At the PETRA III synchrotron facility at DESY, an undulator of 5 m length with 100 mA of current produces a total power of 7.5 kW, with a power density of 250 W/mm² at 28 m from the source. A photon shutter has been designed as a slit system that will block the undulator beam with an integrated vertical shutter function. Figure 9.3 shows the photon shutter system and details of the design parameters. Drawings and thermal stress analysis can be found in Hahn et al. (2004, 2007). The upper and lower jaws are inclined by 4° to the primary beam with a water-cooled absorber made of GlidCop. The tungsten block behind absorbs the high energy beam. The open and closed states of the photon shutter system are controlled by a pneumatic cylinder.

**TABLE 9.3**

<table>
<thead>
<tr>
<th>Properties</th>
<th>GlidCop AL-15</th>
<th>GlidCop AL-25</th>
<th>GlidCop AL-60</th>
<th>OFHC Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point (°C)</td>
<td>1083</td>
<td>1083</td>
<td>1083</td>
<td>1083</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>8.90</td>
<td>8.86</td>
<td>8.81</td>
<td>8.94</td>
</tr>
<tr>
<td>Thermal conductivity (watt/m/K)</td>
<td>365</td>
<td>344</td>
<td>322</td>
<td>391</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (µm/m/°C)</td>
<td>16.6</td>
<td>16.6</td>
<td>16.6</td>
<td>17.7</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>130</td>
<td>130</td>
<td>130</td>
<td>115</td>
</tr>
</tbody>
</table>


**TABLE 9.4**

Temperature and Stress Results of Two Photon Shutters for Canted Undulator Beamlines

<table>
<thead>
<tr>
<th>Case</th>
<th>PS2 (k = 2.76)</th>
<th>PS2 (k = 2.62)</th>
<th>PS1 (k = 2.76)</th>
<th>PS1 (k = 2.62)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak incidental power density (w/mm²)</td>
<td>10.4</td>
<td>9.8</td>
<td>12.7</td>
<td>12.0</td>
</tr>
<tr>
<td>$T_{\text{max}}$ on GlidCop (°C)</td>
<td>248</td>
<td>227</td>
<td>278</td>
<td>255</td>
</tr>
<tr>
<td>$T_{\text{max}}$ on OFHC copper (°C)</td>
<td>163</td>
<td>149</td>
<td>180</td>
<td>164</td>
</tr>
<tr>
<td>$T_{\text{wall}}$ (°C)</td>
<td>129</td>
<td>118</td>
<td>143</td>
<td>131</td>
</tr>
<tr>
<td>$\sigma_{\text{e}}$ (MPa)</td>
<td>347</td>
<td>317</td>
<td>394</td>
<td>360</td>
</tr>
</tbody>
</table>

The SLS PSI machine has electron energy of 2.4 GeV. The photon shutter design at SLS is capable of handling the full intensity power load of 4 kW and a power density of 95 W/mm² from the insertion device. The details of thermal and stress analysis are explained in Chen et al. (2001). The shutter head is a rectangular water-cooled OFHC copper block with embedded water channels. The shutter head is tilted by 3° with a horizontal plane and 15° at each end of the region. The shutter head is moved in the vertical direction by a pneumatic actuator. The test results show that the thermally induced strain will be less than 0.2%, which the photon shutter can withstand.

Several X-ray FEL facilities shown in Figure 9.1 are opening up new doors for exciting scientific research. These facilities are currently in the construction phase, commissioning, operation phase, or upgrade phase. The European X-ray Free-Electron Laser Facility (European XFEL) is under construction in Hamburg and Schleswig-Holstein, Germany, second quarter of 2017 will be commissioning and user operation. This facility will generate extremely brilliant X-rays (peak brilliance = $10^{33}$ photons/s/mm²/0.1% BW) with ultrashort pulses up to 100 fs and with a repetition pulse rate at 4.5 MHz of spatially coherent X-rays with wavelengths down to 0.1 nm. The basic process to generate the X-ray pulses is self-amplified spontaneous emission (SASE), where electron bunches are generated by a high brightness gun, brought to high energy of up to 20 GeV (17.5 GeV is the energy foreseen for the standard mode of operation of the European XFEL facility) through a superconducting linear accelerator and passed through 200 m long undulators, where the X-ray pulses are generated. It will have 2700 pulses/train with a 100 ms repetition rate, as shown in Figure 9.4. For electron energy of 17.5 GeV with photon energy of 12.4 keV, it will have a peak power of 20 GW and an average power of 65 W. The design parameters of European XFEL front-end shutters are described in Sinn et al. (2012). Figure 9.5 shows the photon shutter which is installed in the European XFEL tunnel for SASE1 beamline, which was designed and build by Reuter GmbH Company. The main components of the shutter are a power absorber B₄C (the B₄C [boron carbide] melting point is 2300°C, but carbon segregation to the surface occurs at about 1400°C), a collimator, and a thick tungsten block. The beam comes from left incidence on the B₄C at a 8° grazing incidence. The B₄C has side cooling with copper tubes to absorb the heat load on the B₄C. The absorber B₄C can be moved in and out of the beam path by using a pneumatic cylinder.

### 9.4 Applications of X-ray Shutters

The X-ray shutters described in Section 9.3 provide safety for the users and protect the beamline components. There is one difference between the X-ray safety shutters and an X-ray fast shutter: the X-ray safety shutters should be integrated into the safety interlock system, whereas a fast shutter must not necessarily be integrated into the safety interlock system. There are two types of X-ray fast shutters: (1) a white-beam X-ray fast shutter, and (2) a monochromatic beam X-ray fast shutter. In several
beamlines, especially the protein crystallography beamlines, X-ray topography beamlines, and other beamlines where samples undergo radiation damage given the long exposure time of X-ray beam from synchrotron sources (Kelly et al. 2011), beam exposure must be controlled. In order to control the X-ray beam exposure, several beamlines have been implemented with millisecond-fast shutter opening to provide an accurate and reproducible X-ray beam exposure, in addition to the X-ray photon shutters, whose response times are much slower. For biological and polymer samples at synchrotron sources, it is challenging to systematically control the exposure of the beam, because the damage occurs on a time scale of milliseconds. For studying the dynamics of biological motion, the shutter is required to improve image quality by reducing motion smear, and dose to the sample may be required for ethical, preservation, and safety measures (Brenner and Hall 2007; Holton 2009).

Imaging techniques like standard computed tomography (CT) (Kak and Slaney 1988), X-ray tomography (Morton et al. 1999), and four-dimensional micro-CT (Badea et al. 2009) are commonly used for biomedical imaging. More details about the computed tomography imaging systems can be found in Section III: X-ray Computed Tomography of this book. The imaging of physiological motion at both micro- and macro-scale levels requires X-ray photons of short exposure times at high frame rates, which is not possible without high brilliance of the source. For such types of dynamic imaging, synchrotron sources provide the high brilliance.

Several approaches have been described in the literature for the fabrication and implementation of fast shutters in synchrotron facilities for a monochromatic X-ray beam. For example, (1) choppers based on a rotating crystal with an opening time of 0.23 μs (Norris et al. 1992; Kosciesza and Bartunik 1999; McPherson et al. 2002), (2) choppers based on a rotating cylinder with an opening time of 2.4 μs (McPherson et al. 2000), (3) choppers based on a rotating disc that, in turn, is based on the DC servomotor and frequency-lock and combined with air bearing and an opening time of 2.1 μs (Gembicky et al. 2005), and (4) galvanometer-based fast shutters based on galvanometer-based motion systems with an opening time below 1 ms for monochromatic beams (APS 1-ID beamline).

The FLASH user facility in Hamburg, Germany, produces extremely bright tunable ultrashort laser pulses in the extreme ultraviolet and soft X-ray region (Ackermann et al. 2007). It produces a flux of 10^{13} photons/pulse, with a pulse length of 10 to 50 fs. For experiments related to solid-state physics, X-ray holography needs to select a single pulse. For this purpose, a fast mechanical shutter system has been developed that allows for the selection of individual photon bunch trains and has a repetition rate of ~10 Hz. The details of this design can be found in Tiedtke et al. (2009). Figure 9.6 is a drawing of the mechanical layout of a fast shutter.

The white-beam X-ray topography gives information about the bulk microstructure of the crystal, and the transmitted diffraction image can be recorded to a depth of several millimeters in the material. One important application of white-beam X-ray topography is crystal-based X-ray optics development for structure analysis/crystal orientation and industrial characterization of single crystals and epitaxial materials. White-beam X-ray topography is based on Laue geometry (transmission geometry), and the diffracted Laue pattern consists of diffracted spots. Due to the intense flux from the synchrotron source, the exposure time of the imaging process should be precisely controlled down to the millisecond.

Figure 9.7 shows the white-beam fast shutter at the 1-BM beamline of APS. The fixed-gap aperture of 70 mm horizontally and 5 mm vertically is made of copper and mounted on the flange. Both sides of the flange are connected by bellows to allow the movement of the aperture in the vertical direction. The shutter is driven by a linear actuator. Water cooling has been incorporated into the actuator to improve heat dissipation. More details about fabrication and test results can be found in Kujala et al. (2013) and Macrander et al. (2016). The opening time of the fast shutter is 32 milliseconds, as shown in Figure 9.8.

### 9.5 Commercially Available X-ray Shutters

Sections 9.3 and 9.4 describe the design, implementation, and applications of X-ray shutters at different X-ray light source facilities. This section describes some of the commercially available companies who have designed and manufactured shutters presently used at different synchrotron facilities. Cedrat Technologies (http://www.cedrat-technologies.com/) offers X-ray shutters designed with an aperture size of 0.3 mm × 5 mm (FPS200M series) with an exposure time of 2 ms, 0.7 mm × 5 mm (FPS400M series) with an exposure time of 4 ms, and 1.1 mm × 5 mm (FPS900M series) with exposure time of 10 ms, based on piezoelectric actuators for...
a monochromatic X-ray beam that have been installed at ESRF beamlines in France, APS beamlines in the U.S., Soleil beamlines in France, Diamond beamlines in the UK, SPring-8 beamlines in Japan, and PETRA III at DESY in Germany.

Vincent Associates New York (https://www.uniblitz.com/) offers an XRS series of shutters for X-ray monochromatic beams, designed with attenuation rated to 30 keV using a translational blade mechanism. They are available with an aperture size of 6 mm (XRS6 series) with an exposure time of 9 ms and a maximum operation rate of 50 Hz, 14 mm (XRS14 series) with an exposure time of 35 ms and a maximum operation rate of 10 Hz, and 25 mm (XRS25 series) with an exposure time of 30 ms and a maximum operation rate of 10 Hz.

NatX-ray, Saint Martin d’Hères, France (http://www.natx-ray.com/home.html) builds the X-ray shutters from IR to an X-ray monochromatic beam with an aperture of 12 mm × 12 mm, an exposure time of 17 ms, and a maximum operation rate of 50 Hz. The shutter is based on a stainless steel head mounted on a stepper motor. To open and close the shutter, a 90° rotation is operated. An inductive sensor is placed to allow a homing of the motor at the start. The opening and closing of the shutter is defined by Ethernet with an electrical signal.

Huber X-ray Diffracted Equipment, Rimsting, Germany (http://www.xhuber.de/index.php?id=1&L=1) designs and manufactures X-ray shutters (Module 3100.30) for monochromatic beams with an aperture of 6 mm that can be driven by a transistor-transistor logic (TTL) input signal, and a manually and programmable opening time with an exposure time of <3 ms.

Xia LLC, Hayward, CA, USA (http://www.xia.com/) manufactures X-ray shutters and filter systems (Models PFCU/PF4/PFS2) for monochromatic beams with an aperture of 20 mm × 80 mm that can be moved by pneumatic actuators controlled by electrically operated valves by 50 to 100 psi (3.5–7 bar) of compressed air and with an exposure time of <0.1 s.


Table 9.5 summarizes the commercial companies that currently design and manufacture the X-ray shutters. It also gives the papers published for the design, fabrication, and implementation of X-ray shutters in different light source facilities.

### 9.6 Summary and Conclusion

The X-ray photon shutter is a crucial component for personnel and equipment safety. A fail-safe design and the ability to indicate the open and closed positions are critical. The designs of the X-ray photon shutters at different synchrotron research facilities are mentioned in the previous sections, based on the literature and publications available from the respective facilities. However, several facilities have upgraded their X-ray photon shutters for further optimization according to the needs of their beamlines. As described in the previous sections, there is no standard design for the photon shutter. One has to design the X-ray photon shutter according to their source parameters. Extensive thermal analysis and tests must be performed for the front-end photon shutters, based on the heat load and power density of the photon beam. Nevertheless, detailed thermal analysis must be undertaken for each device to assure that the design of the photon shutter is adequate.

### Acknowledgments

I would like to thank Gary Navrotski, Deming Shu, and Yifei Jaski from APS; Lewis Batchelor, Harald Sinn, Fan Yang, Jan Grünert, and Serguei Molodtsov from European XFEL; and Horst Schulte-Schrepping and Kai Tiedtke from DESY. Also, I would like to thank Kurt Ament from European XFEL for helping me edit this chapter. Finally, I would like to thank Paolo Russo for giving me the opportunity to write this chapter.

### REFERENCES


X-ray Shutters


Meron, M. APS CARS-CAT. SRUFF: A comprehensive package for synchrotron radiation spectral and optics calculations. Based on IDL program, unpublished.


