Radiation Physics Issues for the Advanced Photon Source Upgrade

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Abstract

Argonne's Advanced Photon Source is planning a major upgrade which will significantly increase the brightness of hard x-rays and incorporate advanced beamlines, optics, and detectors. The upgraded facility will feature high charge-per-bunch swap-out injection to the storage ring and an increase in storage ring current from the present 100 mA to 200 mA. Because of the significantly different injection and storage ring parameters, there is a potential for higher losses and thus higher dose rates around the facility. Five issues have been identified for further investigation: (1) higher losses due to high charge per bunch throughout the injection chain (2) losses of injected beam in the storage ring and at other localized loss points (3) stored beam losses in the storage ring (4) increased potential for gas bremsstrahlung along the insertion device beamlines and (5) dose rates around the beam dump for swapped-out bunches. This paper contains a brief summary of the APS Upgrade and discusses progress to date on the radiation physics issues.

1. Introduction

1.1. Advanced Photon Source Upgrade

The APS-Upgrade (APS-U) will be a next-generation synchrotron light source with extreme brightness for hard x-rays due to its low emittance. The storage ring circumference will remain unchanged at 1104 m, but the magnetic configuration of each ring sector will change from a double-bend lattice to a multi-bend achromat (MBA) lattice, as shown in Figure 1. Table 1 gives some of the important parameters for both the present APS and the Upgrade. While the insertion device locations are the same for the two cases, the locations of high beam dispersion will be different, and thus there may be different loss points for the beam. Installation and commissioning, including with-beam testing, is expected to take twelve months.

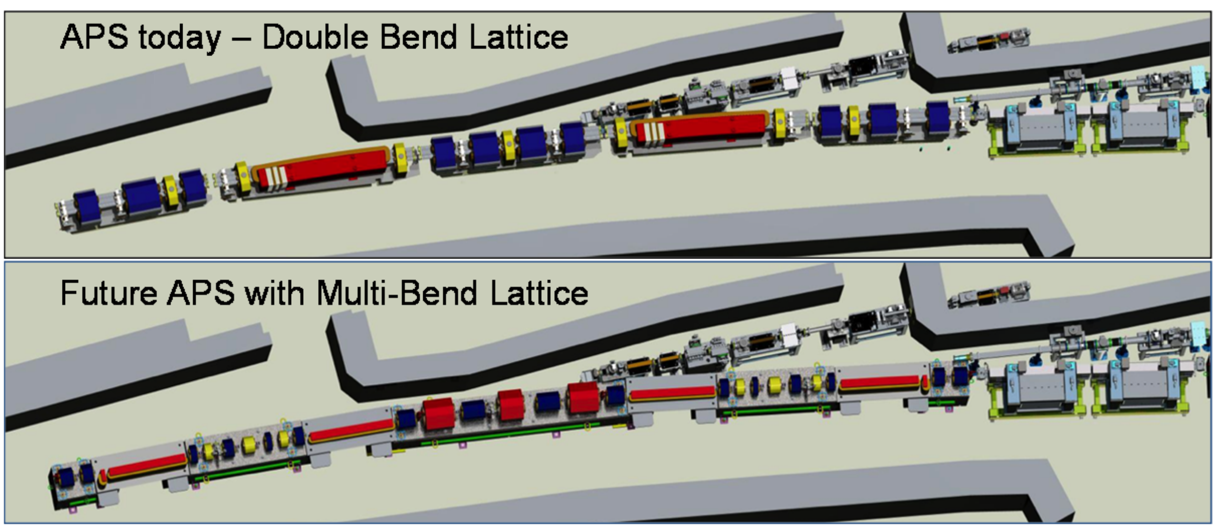

Fig. 1 – Current and future APS storage ring lattice configurations.

The safety analysis for an accelerator facility is performed for a set of conditions called the Accelerator Safety Envelope (ASE), which describes the physical and administrative bounding conditions and controls for safe operation. All safety features (e.g., shielding) must be designed for operation at the conditions of the ASE, even if it is not physically possible to operate the accelerator at those parameters. In this sense the ASE can represent a very conservative set of conditions. Each part of the APS facility has its own ASE. For example, the ASE for the booster synchrotron is 308 W of beam power output (nominally 2 pps x 20 nC/pulse x 7.7 GeV), while the ASE for the storage ring is 9280 J (e.g., 360 mA at 7 GeV). The Accelerator

Safety Envelope will not change for the Upgrade. Another set of parameters, called the Design Performance Goal, lists the conditions under which the facility is expected to normally operate. For the present APS synchrotron and storage ring, these are 84 W (2 pps x 6 nC/pulse x 7 GeV) and 2578 J (100 mA at 7 GeV), respectively. These parameters will increase with the Upgrade. The new Design Performance Goals will be 96 W (1 pps x 16 nC/pulse x 6 GeV) and 4420 J (200 mA at 6 GeV).

Parameter	Present APS	APS-Upgrade
Electron energy (GeV)	7.0	6.0
Stored current (mA)	100	200
Beam lifetime (h)	8	1.9 (timing mode)
		6.7 (324-bunch mode)
Injection type	Top-up	Swap-out
Charge per bunch (nC)	1-2	15.3 (timing mode)
		2.3 (brightness mode)

Table 1 – Selected parameters for the present Advanced Photon Source and the APS-Upgrade. Lifetimes for APS-Upgrade beams are 10-th percentile lifetimes with round beams.

1.2. Dose Rate Goals

Radiation dose rates due to operation of the APS-Upgrade must meet the same radiological protection standards as other accelerator facilities in the United States. Table 2 gives the dose rate goals in the US and at Argonne for new or significantly modified facilities. The typical design objective is one-half of the goal to provide an added safety margin due to uncertainties in codes, data, etc. (e.g., design to 5 mSv/y for a goal of 10 mSv/y). APS users are not considered radiation workers, and they are limited to the same annual dose as members of the general public. For the experiment hall and other areas normally accessible to users, the shielding will be designed to a dose rate of 0.25 Sv/h. Dose measurements over the APS facility lifetime have shown that the average radiation worker at APS (the radiation worker designation is due to work with sealed sources, not to exposure from the beam) receives less than 1 mSv/y. Area dosimeters in the APS experimental hall are changed with each run cycle (3 months of experiments followed by 1 month for maintenance), and read less than the detection threshold of about 0.1 mSv (gamma) and 0.2 mSv (neutron).

Parameter	Annual rate (mSv/y)	Hourly rate (μSv/h)
US limit for radiation workers	50	25
US goal for new or significantly modified facilities	10	5
Argonne design goal for new or modified facilities	5	2.5
APS – maximum rad worker dose	5	2.5
APS – average rad worker dose	2	1.0
Non-rad workers and general public	1	0.5

Table 2 – Dose rate goals for radiation workers and the general public.

2. Source Terms

The existing shielding for the APS was designed based on empirical equations for the dose rate due to photons (bremsstrahlung) and neutrons, with the effects of shielding taken into account by exponential attenuation. As the first step in the shielding design process, we are making comparisons between the empirical source terms and the results of modern computer simulations, which were not available at the time the present APS shielding was designed.

The source term for bremsstrahlung dose (µSv/J) used for the original design of the APS shielding is [1]

$$H_B(\theta_B) = 167E_0(2^{-\theta/\theta_{1/2}}) + 8330(10^{-\theta/21}) + 250(10^{-\theta/110}) \tag{1}$$

where E_0 is the electron beam energy, θ is the angle with respect to the incident electron beam, and $\theta_{1/2}$ = $100/E_0$ (degrees). The first term accounts for the very highly forward peaked bremsstrahlung due to the highest energy electrons, while the remaining two terms represent the dose rate at larger angles.

The source term for neutron dose (µSv/J) used for the original design of the APS shielding is [1]

$$H_N(\theta) = A + \frac{B}{1 - 0.75\cos\theta} + \frac{C}{(1 - 0.72\cos\theta)^2} \tag{2}$$

In this equation, A, B, and C are constants that depend on the target material, and θ is the angle measured with respect to the incident electron direction. The first term represents neutrons arising from the giant resonance process, which are largely isotropic and increases with higher Z. The second and third terms represent medium-energy and high-energy neutrons, which are forward peaked and higher for lower Z. Values of the constants *A*, *B*, and *C* are given in Table 3 for materials commonly encountered at the APS.

Constant	mechanism	Al	Fe	Cu	W	Pb
A	giant resonance	0.208	0.328	0.353	0.654	0.700
B	medium energy	0.0614	0.033	0.033	0.020	0.020
C	high energy	0.0154	0.0083	0.0083	0.012	0.012

Table 3 – Parameters for the empirical neutron source term.

The empirical source terms are compared in Figure 2 to the results of Monte Carlo simulations using MCNP6 [2] for 6 GeV electrons incident on a 14 cm long by 10 cm diameter copper cylinder. The source terms depend on the cylinder dimensions, and in this case the dimensions were chosen to roughly maximize the yield of neutrons and high-energy photons. This corresponds to a length of about 10 radiation lengths and a radius of about 3 Moliere radii. This is also the approximate size of the transition piece at the entrance to an insertion device. The empirical source term for photons agrees well with the simulation results at the very forward angles, but is a factor of ten higher over most of the angular range. Since the dose rate outside the shielding of the storage ring will depend mostly on the radiation emitted at 90°, this leads to an over-estimation of the dose rate. The empirical equation for neutron dose rate shows better agreement with the simulation results and is only about 20% high at 90 degrees. Similar results have been obtained for electrons incident on aluminum, which is used as the vacuum vessel in parts of the storage ring.

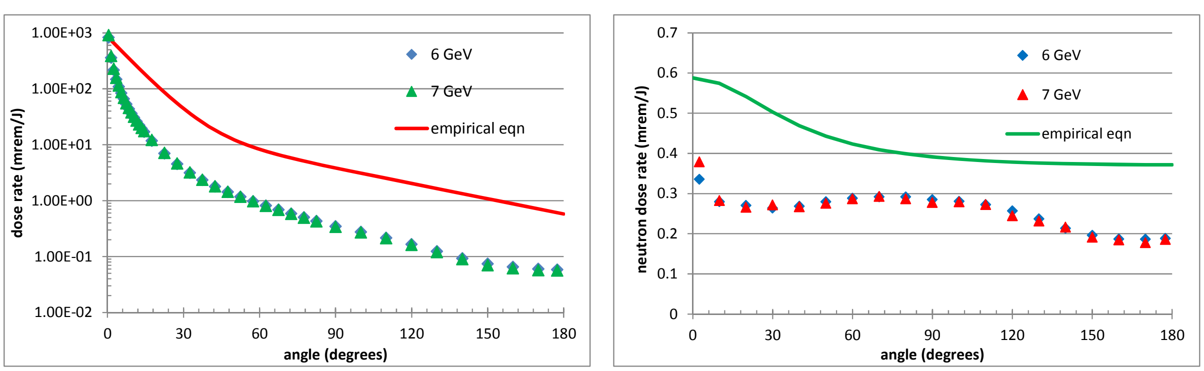

Fig. 2 – Comparison of empirical photon and neutron source terms to results of MCNP6 simulations.

3. Radiation Safety Issues for the APS-Upgrade

Five issues have been identified as potential areas of concern for the APS Upgrade. Each of these issues represents the potential for a source term to change in magnitude or location (or both) and will be discussed separately below. However, in the process of developing the radiation safety plan for the Upgrade, the potential for radiation exposure throughout the facility will be investigated in detail.

3.1. High-Charge Injection

The high-bunch-charge required for the 48-bunch mode in the storage ring will require injection of bunches having charge as high as 20 nC. The present injection scheme has electrons accelerated in a linac and accumulated in the Particle Accumulator Ring, then injected into the booster synchrotron for acceleration to their final energy, and finally transported into the storage ring. The Accelerator Physics group is conducting experiments and simulations to determine the loss points for beam through the injection cycle. These results will be combined with existing measured dose rates to estimate the dose rates due to high-charge injection and the need to add or relocate shielding.

3.2. Dose due to Injected Beam Losses

Beam injected into the storage ring can be lost at the injection point or in the first few turns around the storage ring. Calculations for the existing shielding assumed that the synchrotron was injecting continuously into the storage ring at the ASE limit of 308 W. 20% of the injected power was assumed to be lost at the injection point, and 20% of the remaining power lost at the first insertion device. For an assumed injection duty factor of 10%, all locations around the injection region had dose rates less than 2.5 μSv/h, the dose rate design obejctive.

Beam injection simulations for the APS-Upgrade indicate that the fraction of injected charge lost in the high-bunch-charge mode, for all locations around the storage ring, is expected to be around 1%. Simulations of beam orbits following injection will indicate the locations at which beam is expected to be lost. The source terms developed from these losses can be used to assess the adequacy of shielding in those areas. The injection duty factor would be 6.67%, assuming a beam lifetime of 1.9 h and replacement of a bunch when it falls to 90% of the initial charge. Since the APS-U design performance goal of 96 W (1 pps x 16 nC/bunch x 6 GeV) is not much higher than the present design performance of 84 W, and the injection duty factor and fraction of beam lost at injection are both smaller for the Upgrade, we expect that dose rates due to loss of injected beam will be much less than at present.

3.3. Dose due to Stored Beam Losses

Stored beam can be lost uniformly around the storage ring due to processes that continually scatter particles out of a bunch, or lost locally in regions of small aperture such as the transition pieces to insertion devices. The loss rate for particles from the MBA lattice will be higher than for the present APS storage ring since the stored current will be larger and the beam lifetime shorter.

For uniform losses, we can use the stored energy and the beam lifetime to calculate the beam loss in J/h/m. These loss rates, and the results of calculations for uniform beam loss and a shield wall that follows the beam orbit (rather than the actual ratchet wall), are given in Table 4. The beam orbit is assumed to follow a circular path instead of the actual trajectory, and the outboard shield wall (56 cm of high-density concrete) is assumed to be a constant 50 cm away from the beam orbit. Moe [1] calculated the dose rate outside the storage ring bulk shielding for a uniform loss of the present APS beam assuming an 8-h lifetime, which is typical of present operation, and the empirical source terms given in Equations 1 and 2. At the conditions of the accelerator safety envelope (9280 J stored energy), this gives an energy loss of 1.05 J/h/m assuming top-up operation (where the stored current is kept roughly constant) or 0.59 J/h/m if the beam is allowed to decay to 1/e of its initial value before being restored to the full value.

Case	stored energy (J)	beam lifetime (h)	loss rate (J/h/m)	dose rate (mrem/h)
Present APS	9280	8	1.05	0.04
	2578	8	0.292	0.011
APS Upgrade	9280	1.9	4.424	0.046
	9280	6.7	1.255	0.013
	4420	1.9	2.107	0.022
	4420	6.7	0.597	0.0062

Table 4 – Dose rates due to uniform losses of stored beam in the APS storage ring.

The calculations for the Upgrade storage ring were performed with MCNP6, using the source term discussed above for electrons incident on a 14 cm long x 10 cm diameter copper cylinder. The dose rates are smaller than those from the earlier calculation due to the smaller dose rate per incident electron. In addition, the dose rates for the APS Upgrade do not include any effects of shielding due to accelerator components, so in practice they will be even lower.

Dose rates due to localized losses will be calculated using a MCNP6 model for the storage ring shielding, shown in Figure 3. These calculations will use source terms (location and magnitude) from simulations of beam transport in the storage ring, and are still at an early stage.

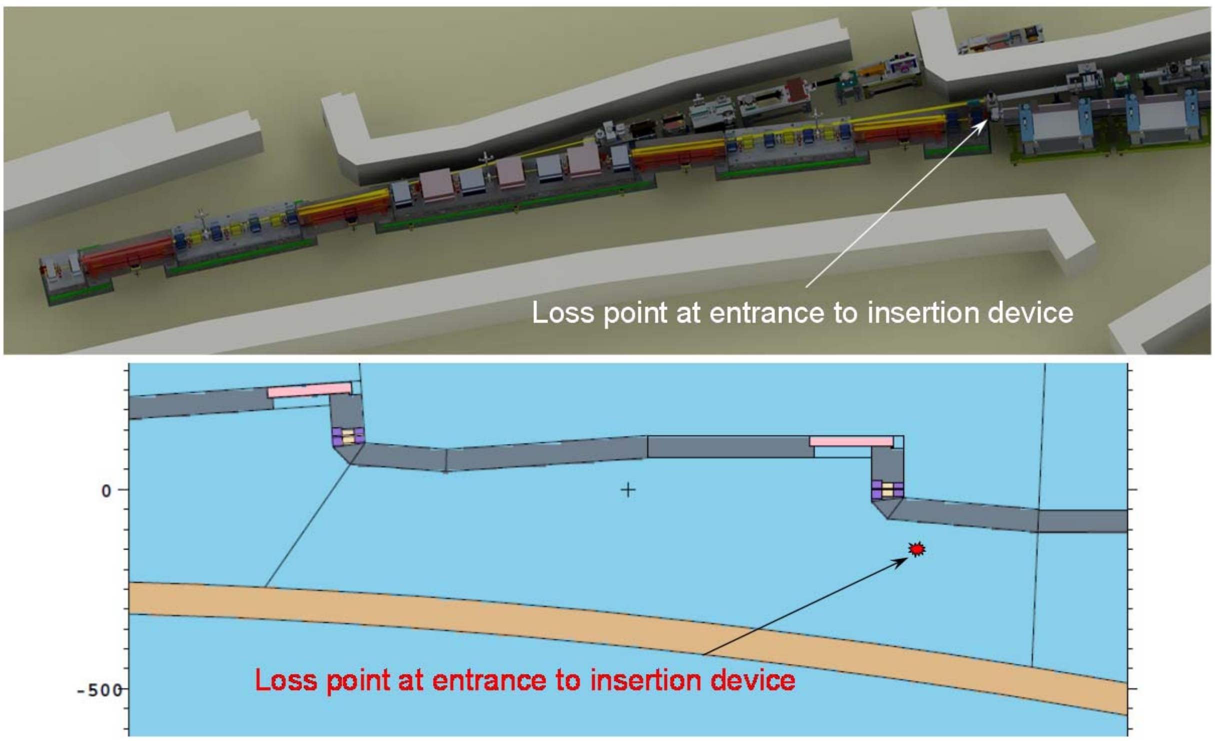

Fig. 3 –MCNP6 model of the storage ring bulk shielding with a loss point at the entrance to an insertion device.

3.4. Gas Bremsstrahlung

The collision of electrons with residual gas in the straight sections of the storage ring will be a significant source of bremsstrahlung. This bremsstrahlung can cause doses outside the shielding because it can pass through the same openings used to bring synchrotron radiation into the experimental areas. The radiation yield depends on the pressure and composition of the residual gas. The design goal vacuum pressure for the APS-U is 2 nT, which is higher than the present vacuum level of 1 nT. However, this will be offset by the fact that the straight sections will be a factor of two shorter. Simulations by the APS vacuum group indicate that the residual gas in the APS-U will have significant quantities of CO and CO_2 compared to the present storage ring, which is dominated by H_2. A higher effective Z for the residual gas would increase the radiation yield from gas bremsstrahlung. Detailed studies will require further refinement of the vacuum system design.

3.5. Swap-Out Beam Dump

For swap-out injection, entire charge bunches will be removed from the storage ring and replaced with new injected bunches. The dumping of this charge into a beam stop will generate significant secondary radiation (both bremsstrahlung and neutrons). Assuming a beam lifetime of 1.9 h, a bunch will drop to 90% of its initial charge after about 720 s. This means that 90% of the stored energy in the SR (9280 J at the ASE) will be deposited into a beam dump every 720 s, for an average power of 11.6 W. At the design performance goal, the beam dump would receive about 0.9 x 4420 J / 720 s = 5.5 W. Since the shielding in the injection area is already sufficient for a continuous loss of 62 W, the existing shielding should be adequate to protect against this new source term. The location of and shielding around this beam dump should be chosen consistent with ALARA considerations.

4. Summary

The APS-Upgrade will have different operating parameters from the present accelerators and storage ring. Specifically, there will be an increase in injected charge per bunch, increased stored current in the storage ring, slightly lower electron energy, and shorter beam lifetimes. Five areas of potential concern have been identified that may lead to source terms that are either larger or in different locations (or both). Of these, the ones with the greatest potential to increase dose rates are the loss of high-charge bunches in the injection chain, the loss of stored beam in the storage ring and the generation of gas bremsstrahlung. Doses due to loss of beam injected into the storage ring and due to the dumping of swapped-out beam are expected to be low based on comparison to the existing facility. Since the accuracy of source terms for all secondary radiations is important, we are working with the accelerator physics group to determine beam loss magnitudes and locations. Monte Carlo radiation transport simulations will be supplemented with empirical calculations to determine the effectiveness of the existing bulk and local shielding, and supplemental shielding will be added or relocated as necessary. We are also considering the use of beam scrapers to make beam losses occur in areas where it is easier to provide additional shielding if needed.

Acknowledgement

Argonne National Laboratory is supported by the US Department of Energy's Office of Science under contract number DE-AC02-06CH11357.

References

[1] H. J. Moe, "Radiological Considerations for the Operation of the Advanced Photon Source Storage Ring - Revised", Advance Photon Source report LS-295 (Sept. 1997).

[2] D. Pelowitz, ed, "MCNP6 User's Manual", LA-CP-13-00634, Rev. 0 (May 2013).