Title
Advanced light source-Upgrade accumulator-ring gas bremsstrahlung production

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Title. Advanced Light Source – Upgrade Accumulator-Ring Gas Bremsstrahlung Production

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ABSTRACT
Lawrence Berkeley National Laboratory is designing a new electron synchrotron for scientific research using synchrotron radiation. An upgrade of the Advanced Light Source (ALS) would position the nation to retain its international competitiveness in the soft x-ray sciences. The ALS is a 1.9 GeV storage ring operating at 500 mA of beam current. It is optimized to produce intense beams of soft x-rays, which offer spectroscopic contrast, nanometer-scale resolution, and broad temporal sensitivity. Upgrading the ALS storage ring from a triple-bend-achromat to a multibend-achromat (MBA) lattice design will provide a soft x-ray source that is up to 100–1,000 times brighter than today's ALS and will provide a significantly higher fraction of coherent light in the soft x-ray region than is currently available at the ALS. The upgraded ALS will offer the highest coherent flux of any existing or planned storage-ring facility, worldwide, up to a photon energy of 3.5 keV. The addition of an accumulator ring that enables on-axis, swap-out, recovery, and exchange of bunch trains is required to achieve this coherence and brightness. Analysis of the radiation generated and shielding required by the addition of this new accelerator is presented in this paper.

KEYWORDS
bremsstrahlung, synchrotron, shielding, radiation, mcnp

1 Introduction

This study evaluates gas bremsstrahlung (GB) production in the accumulator ring of the planned Advanced Light Source – Upgrade (ALS-U). The ALS-U facility will operate with a 2-giga-electronvolt (GeV) electron beam and a maximum stored beam current of 500 milliamperes (mA). GB evaluations for high energy electron accelerators are necessary to be performed during facility design and construction in order to properly mitigate the resulting radiation.

ALS-U Radiation Physics used the software program Monte Carlo N-Particle 6.1® ("MCNP6")[1] code to study three radiation source terms, including the software's bbrem specialized high-energy bremsstrahlung photons biasing, the produced spectrum, dose rates, and adequacy of current shielding associated with the expected GB. This software is well benchmarked against other available software and has been shown to be reliable for many different types of nuclear and radiological applications [1][2][3][4].

[1] MCNP® and Monte Carlo N-Particle® are registered trademarks owned by Los Alamos National Security, LLC, manager and operator of Los Alamos National Laboratory.

2 Description of Accumulator Ring

The accumulator ring has two main functions, as follows: 1. To damp the beam emittance before injection into the small storage-ring dynamic aperture. 2. To store the beam for top-off in between swap-outs.

During operation of the upgraded ALS, the storage ring will contain about 10 bunch trains (each in turn containing about 25 bunches spaced 2 nanoseconds [nsec] apart), and the associated accumulator ring will contain one bunch train. The emittance of the beam in the accumulator will be approximately 2 nanometers (nm) rad (similar to the current ALS). Approximately once a minute, a single storage-ring bunch train will trade places with a single accumulator-ring bunch train. Fast kicker magnets will generate a pulse, sending a train from the storage ring to the accumulator. At the same time, the accumulator train will be moved to the storage ring. [5] Figure shows the paths of the bunch swaps between the accumulator-ring and storage-ring trains.

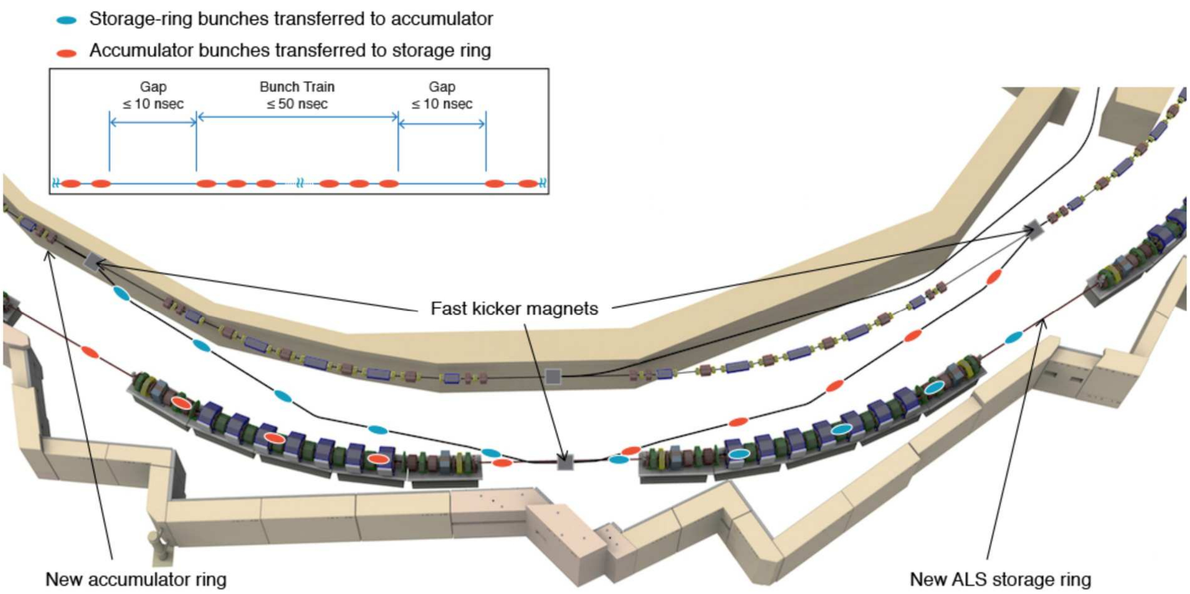

Figure 1. Illustration of bunch train swap-out between the storage and accumulator rings. A train of fresh bunches (red) is injected into the storage ring while simultaneously, a train of spent bunches (blue) is extracted. The "in" and "out" bunches will cross in the fast kicker installed on the storage ring [3]

Between swap-outs, the train in the accumulator will be topped off by the existing LINAC/booster injector, similar to the current top-off operation of the storage ring. By swapping a storage-ring bunch train that has lost a portion of its current with the topped-off bunch train from the accumulator, the overall current in the storage ring will be maintained at 500 mA.

The most natural choice is to place the accumulation injection section across the current ALS injection section (corresponding to the ALS-U straight section with the swap-out fast kicker), aligning the layout phases of the two 12-fold periodic rings. The accumulator is planned to be anchored to the interior wall of the existing storage-ring tunnel, design emphasis is placed on attempting to minimize the magnet weight and ease the requirements on the support system.

3 Radiation Source Term

GB will exist throughout the entire accumulator ring system as electrons collide with molecules of air located within the vacuum chamber. The amount of GB produced will vary linearly with the length of a straight, and with pressure, beam current, and electron energy.

3.1 Source Term Spectrum

GB is often estimated to have a 1/*k* energy spectrum (with *k* denoted as the photon energy to distinguish it from the electron beam energy) [6]. The spectrum extends essentially from zero to the kinetic energy of the stored electrons. The angular distribution is highly forward-peaked having a characteristic angle (i.e., a "1/e" angle) of 0.511/E in radians for electron beam energy E (MeV). For ALS-U's 2 GeV electron beam, the characteristic angle is 0.256 mradians.

Monte Carlo methods were used to test the appropriateness of the 1/*k* assumption. MCNP6 was used to generate these alternate source terms. Two source terms were generated by MCNP6. The bremsstrahlung process generates many low-energy photons, but the higher-energy photons are often of more interest. The first source term is the standard MCNP6 physics database source that did not include use of variance reduction card BBREM. The second source term includes BBREM variance reduction.

BBREM biasing within MCNP6 results in a harder bremsstrahlung photon beam as the result of increased sampling of higher energy electrons within specified materials. This bias increases the enhancement of the bremsstrahlung photon energy sampling gradually up to the specified electron source energy. This also increases the total amount of bremsstrahlung photons and secondary electrons cascades as a result. The efficacy of the bbrem variance reduction has been demonstrated to be an effective bias as compared to its analog [7]. However,this technique does significantly increase computer simulation time as a result of increased secondary particles.

As shown on Figure 2, the 1/*k* source term produces the largest high-energy fraction of bremsstrahlung photons of the three. The larger fraction of high-energy photons results in higher effective dose rates and more penetrating radiation that is more difficult to shield. It is noted that the use of MCNP6 BBREM variance reduction nearly approximated the 1/*k* spectrum at larger energies of interest and led to a large reduction in the sampling error associated with the simulation at high energies; see Figure 3. These sampling errors for source terms are commonly desired to be below 0.20 and can significantly affect the results as the produced source term carries through the entire simulation.

Use of the 1/*k* spectrum is also more conservative because the angular distribution of GB with the direct generation method is broader due to multiple scattering, resulting in bremsstrahlung with wider polar angles and lower flux on target at long distances, such as between the accumulator ring source and the storage-ring shield wall. The 1/*k* source will be used for the remainder of this study to remain more conservative.

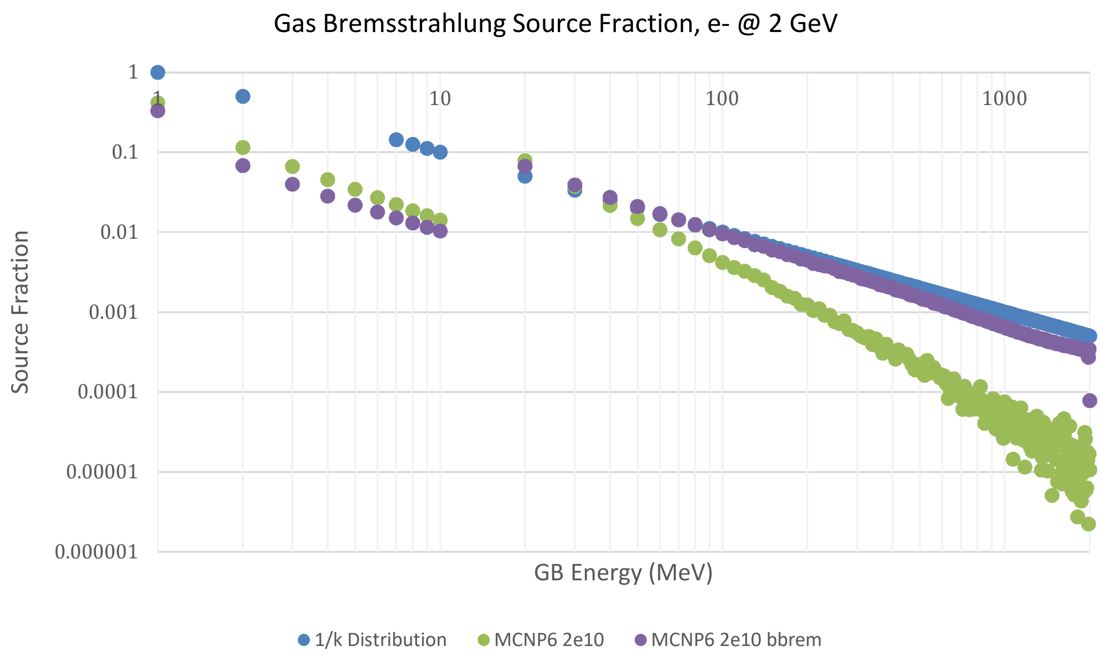

Figure 2. MCNP6 gas bremsstrahlung source fraction indicates 1/k and bbrem methods produce comparable results

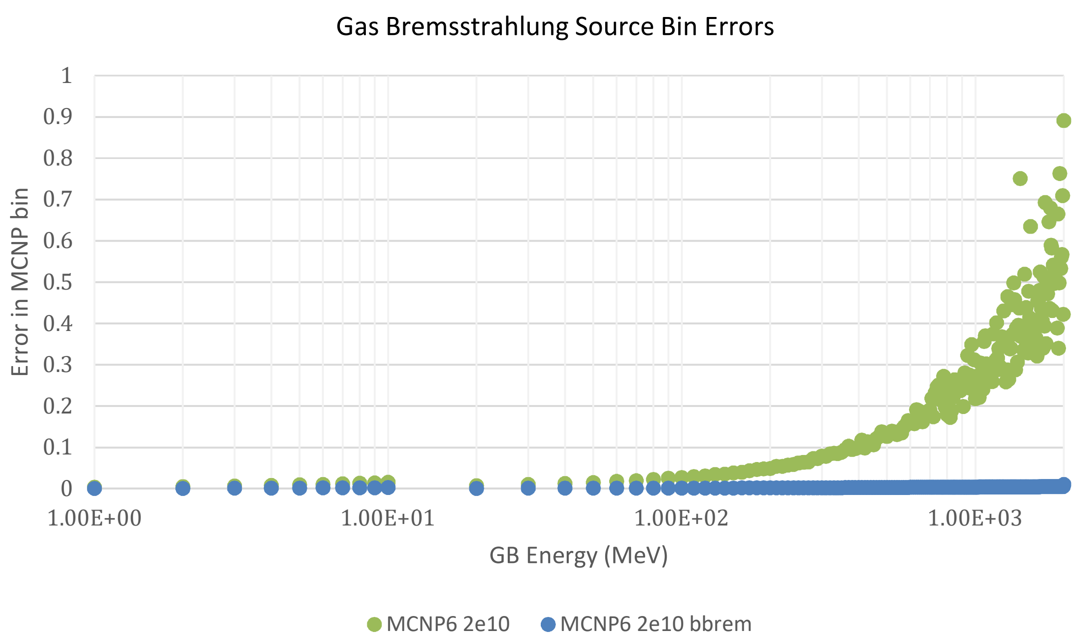

Figure 3. MCNP6 gas bremsstrahlung binning errors showcases the efficacy of bbrem variance reduction

3.2 Source Term Parameters

The vacuum pressure within the accumulator ring system is expected to vary within sections of the accumulator ring, as well as to decrease with increasing runtime of the accelerator due to outgassing of materials. The expected vacuum pressure after 72 amp-hours of beam, representative of the commissioning phase of ALS-U, is conservatively estimated at 5.3x10^{-10} bar. After 1,000 amp-hours, representative of on-going top-off operations of ALS-U, this is expected to drop approximately two orders of magnitude [8].

The area following a straight will result in the largest dose rates as the GB tangentially exits the system. The location of the highest dose rate will be the end of a 4.5-meter straight that is followed by an additional 1.33 meters along the same axis before the electron beam is diverted by a dipole magnet. The straight is preceded by 1.33 meters of on axis vacuum length. This provides 7.168 meters of mass thickness of GB production material.

A fraction of the total electron beam energy stored within a synchrotron ring is converted into GB power. The fraction of that energy converted is directly related to the mass thickness of the air in the arc section that the stored electrons pass through. Equation 1 gives the fraction of bremsstrahlung power that is generated (Fbrem) for the accumulator ring straight, with the parameters provided in Table 1.

$$Fbrem = \frac{L \times p \times P}{Xo} = \frac{716.8 \times 1.205\text{x}10-3 \times 5.26\text{x}10-10}{36.818} = \mathbf{1.235x10-11} \qquad (1)$$

Table 1. Accumulator-Ring Electron Beam Parameters Used to Calculate GB

Parameter	Value	Unit
Electron energy, E	2	GeV
Beam average current, I	46	mA
Single-bunch current	1.76	mA
Vacuum pressure$_{72amp\text{-}hr,}$ P	5.3e x10^{-10}	bar
Radiation length of air, X_o	36.818	g/cm^2
Effective length, L	716.8	cm
Air density, *p*	1.205 x10^{-3}	g/cm^3/atm

The ALS-U accumulator ring has a total stored beam power of 0.092 GW (46 mA × 2 GeV). Thus the GB power is calculated in Equation 2.

$$GB\ Power = I \times E \times Fbrem = 46 \times 2 \times 1.235\text{x}10-11 = \mathbf{1.136x10+3}\ \boldsymbol{uW} \qquad (2)$$

The total GB energy distribution of a 1/*k* fluence is provided on Figure 4. The total calculated output of the 1.136 x10^3 *u*W spectrum is **5.54 x10^7 photons per second** with a mean energy calculated to be 0.128 GeV.

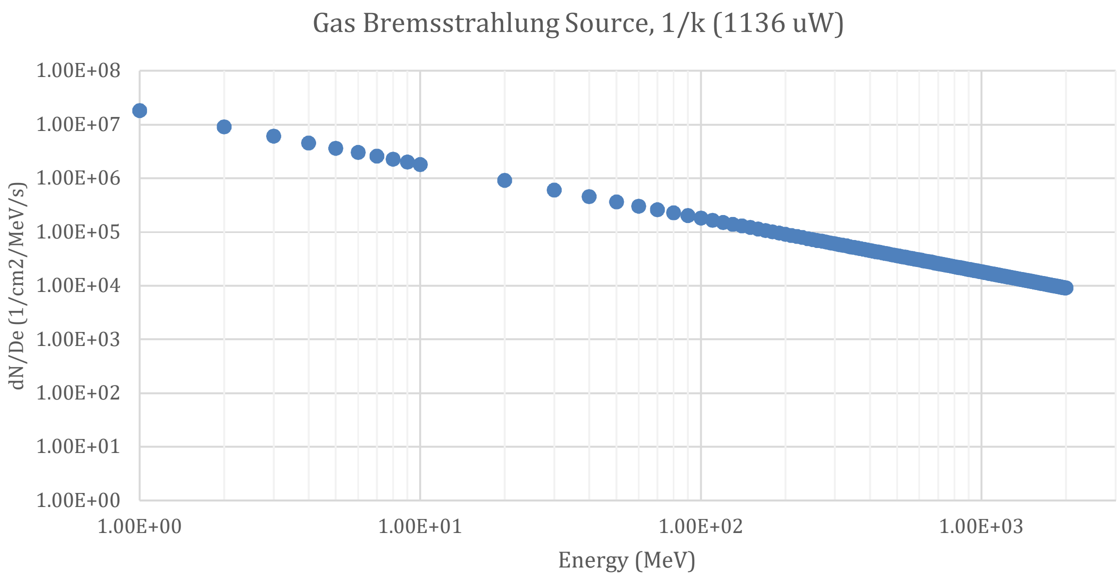

Figure 4. Total GB source fluence produced in the accumulator ring straight

4 MCNP ENVIRONMENT AND RESULTS

In order to characterize the dose rate resulting from GB, a simple model was developed in MCNP6. The transport model was based on available schematic and technical data for ALS-U, and the geometry and placement of components is subject to change. For radiation transport modeling purposes, the accumulator-ring components were broken down into individual connecting cells in an MCNP6 environment.

4.1 Dose Rates Exiting the Vacuum Chamber

In order to characterize the GB dose rates expected upon exiting the vacuum chamber wall (0.8 mm), a simple 1 cm^3 F4 tally, which averages the flux over a large enough cell to reduce result variance due to sampling, was placed on axis with the straight. No collision with the H-gradient dipole magnet is assumed. ICRP 21 photon flux-to-dose rate conversion factors were used as identified by [9] and [10].

Photon Dose Rate Exiting the Vacuum Chamber = **546.3 rem/hr $\pm$ 0.05 rem/hr**

4.2 Dose Rates Following Collisions with Accumulator Ring Components

Following production of GB, the photons will tangentially exit the accumulator ring system through the vacuum chamber wall and outward beyond the H-gradient dipole magnet. Depending on beam positioning, these photons will collide with a downstream SD-sextupole magnet, a downstream quadrupole magnet, or both; see Figure 5. However, this study assumes no contact by the photons with the small ion pump that follows the SD-sextupole magnet. The electrons will be steered by the dipole magnet and remain within the vacuum chamber.

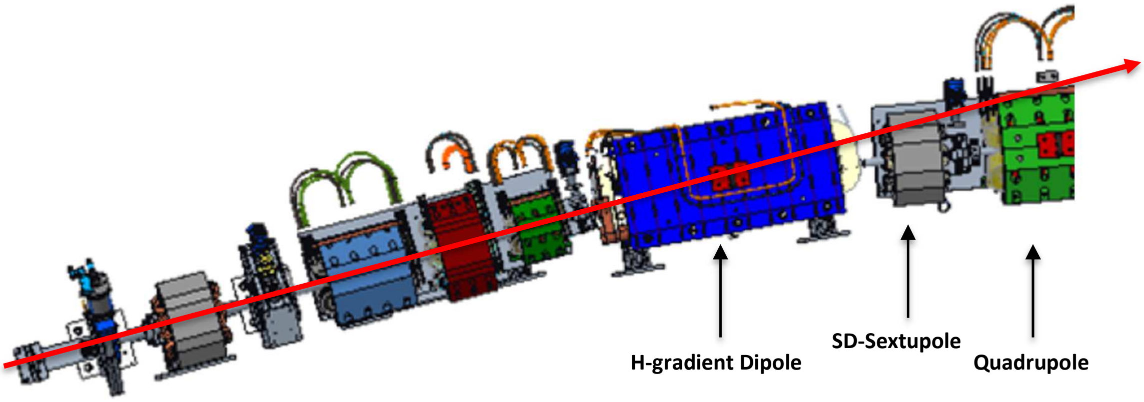

Figure 5. GB production will tangentially exit the accumulator ring (red arrow) through an H-gradient dipole magnet while the accelerator electrons are steered away.

Assuming the beam position is limited to the lower- diameter aperture following the straight (circled on Figure 6), the beam will collide with either the SD-sextupole magnet or the quadrupole magnet in the achromat.

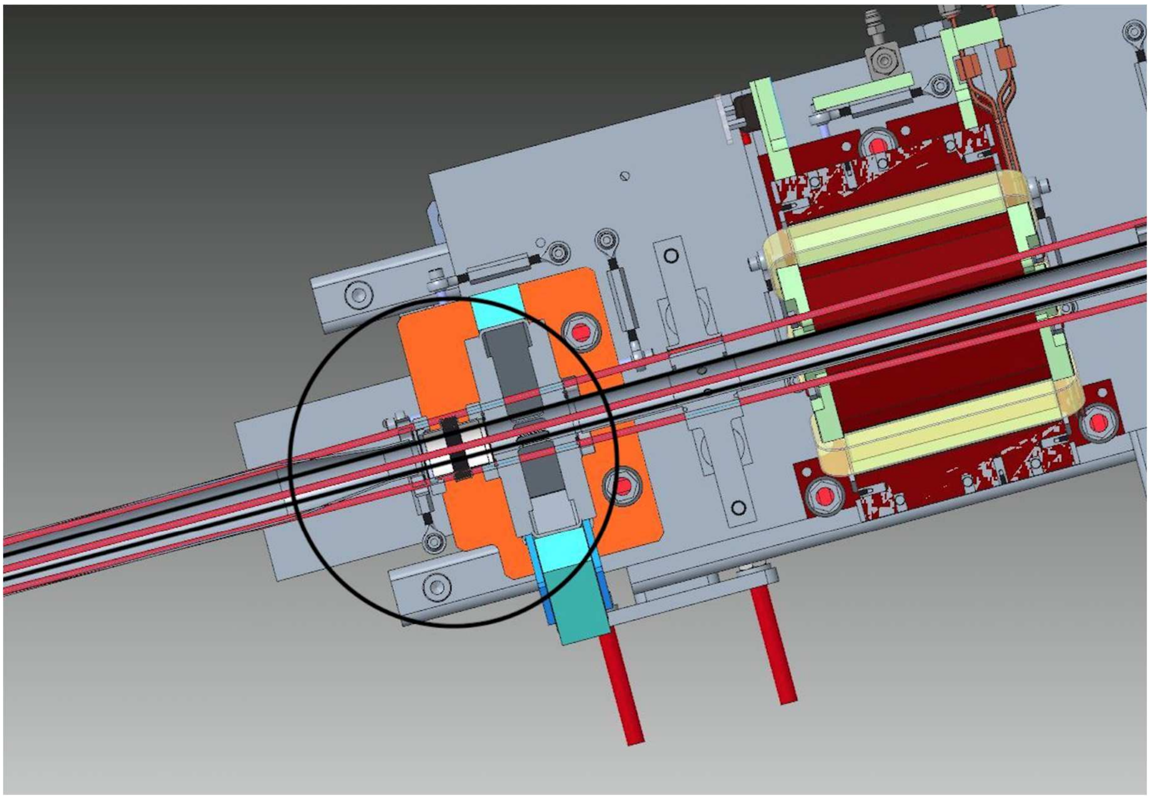

Figure 6. GB ray trace defining a limiting aperture in black lines

Figure 7 shows that if the beam is limited to the aperture defined on Figure 6, the beam position will reduce to the lines shown as 2, 3, or 4. These beam paths will result in differing amounts of interaction with the beamline components A (SD-sextupole magnet) and B (quadrupole magnet).

The most conservative position (#2) results in 18.86 cm of the SD-sextupole magnet colliding with the GB, with the quadrupole missing the interaction pathway. The least conservative position (#4) results in no collisions with the SD-sextupole magnet, but 32.57 cm of interaction pathway with the quadrupole magnet. The magnets are modeled as a cylinder of varying length composed as solid iron

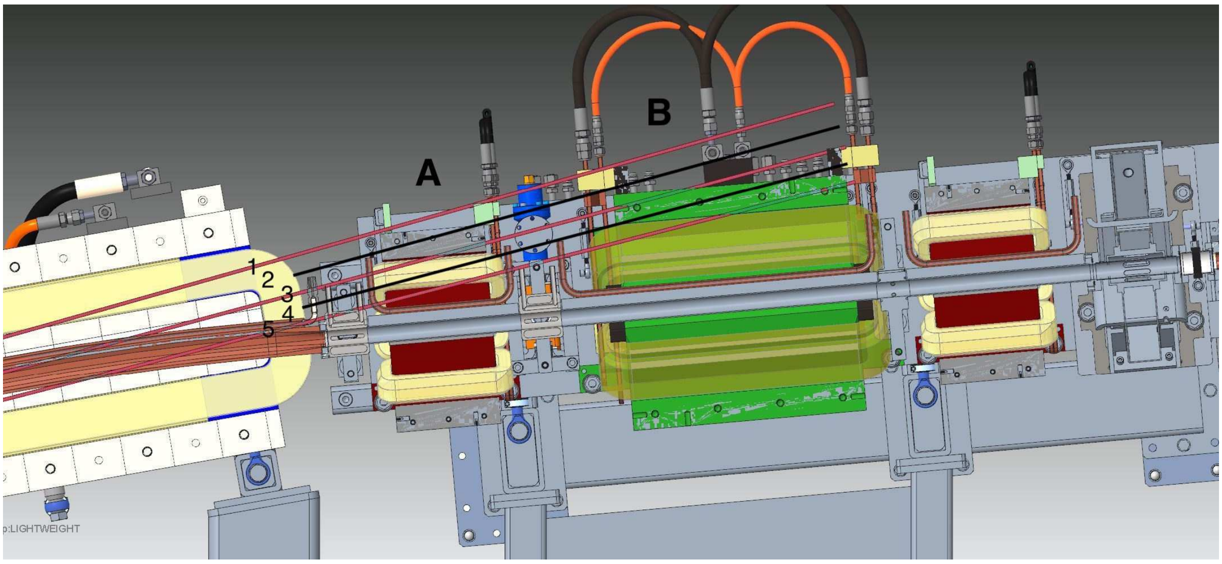

Figure 7. GB interaction pathways by beam position

4.3 Dose Rates at the Storage-Ring Shield Wall

The ALS radiation shielding enclosures are constructed using both cast-in-place concrete structures and precast (removable) roof panels and wall blocks. Linac-vault walls are a minimum of 4 feet thick, as is the vault roof. Booster-synchrotron shielding is cast in place; the tunnel walls are a minimum of 2.5 feet thick, as is the tunnel roof. Removable roof blocks are provided in three locations around the booster for access to equipment and for maintenance.

The storage ring has a fixed (cast-in-place) inner wall and a removable (precast) outer wall section and roof section around its entire circumference to facilitate beamline egress from the tunnel. However, the storage-ring tunnel walls are nominally 1.5 feet thick; the roof of the storage ring is 1 foot thick. In some locations, the storage-ring shield wall and roof thicknesses differ from the nominal values, and in some locations lead shielding is added. This lead shielding is present at the ratchet walls at thicknesses between 3 and 4 inches.

This study assumes the GB has direct incidence upon a 3-inch-thick (7.62 cm) lead shield, immediately followed by a 1.5-foot-thick (45.72 cm) concrete shield wall, located 12.9 meters down the X-axis from the rear of the SD-sextupole magnet. This represents a worst-case scenario given the additional shielding located at some portions of the storage ring.

Table 2 provides a summary of the evaluated effective dose rates for ALS-U accumulator-ring GB. The MCNP calculations do not take credit for any areas of additional shielding provided by lead or thicker shield walls. As such, the real-life conditions may be even lower. The beam paths in the table refer to those established in Figure 9, GB interaction pathways by beam position. As long as the beam path can be restricted to the defined aperture, beam path #2 and beam path #4 represent the highest (most conservative) and lowest (least conservative) dose rates, respectively, as calculated on the opposite side of the storage ring wall. These are below the radiation area posting requirement of 5 mRem/hr and are acceptable for safe user operation of the ALS (ALS-U) accelerator.

Table 2. Accumulator-Ring Effective Dose Rates Due to GB at Different Locations

Location	Pressure (torr)	Effective Dose Rate (Rem/hr)
Post AR Vacuum Chamber	4.00×10^{-7}	546.3 ± 0.01%
Beam Path #1 (no magnet collisions)	4.00×10^{-7}	0.345 ± 13%
Beam Path #2 (most conservative within defined aperture)	4.00×10^{-7}	1.15×10^{-3} ± 29%
Beam Path #2 (1000 A-hrs)	7.70×10^{-9}	2.89×10^{-5} ± 22%
Beam Path #4 (least conservative within defined aperture)	4.00×10^{-7}	3.2×10^{-5} ± 25%
Beam Path #4 (1000 A-hrs)	7.70×10^{-9}	6.15×10^{-7} ± 25%

5 SUMMARY

This paper summarizes the results of the gas bremsstrahlung calculations for the upcoming accumulator ring. These results conclude that the current shielding is adequate and that no special shielding or posting precautions should necessary during ALS-U start-up with regard to the accumulator-ring GB production based on the 72-amp-hour pressures if the electron beam can be limited to the aperture defined in Figure 6.

Note that the effective dose rates calculated for this simulation represent the gas bremsstrahlung produced by the accumulator ring only based on conditions present at 72 amp-hours. Pressure conditions prior to that remain unknown. By 1,000 amp-hours, dose rates are expected to drop by a factor of 52 (4 x10^{-7} torr assumed pressure dropping to an average of 7.7 x10^{-9} torr). As the pressure drops, dose rates will decrease linearly.

Acknowledgement

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