Radiation Physics Issues for the Advanced Photon Source Upgrade

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Outline of Presentation

- Description of Advanced Photon Source Upgrade (APS-U)
- Dose rate goals for the APS-U
- Discussion of important radiation safety issues
- Source terms
- Technical approach to solutions
- Summary

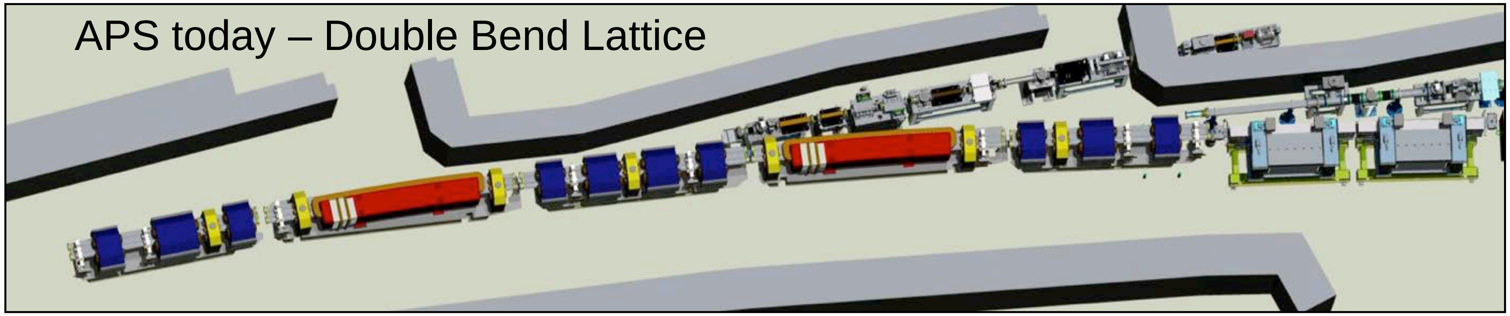
- In particular, we are trying to answer the questions
  - What effects would the new storage ring and injection scheme have on radiation source terms at the APS?
  - What additional shielding would be needed to mitigate new hazards?
- Adequate shielding is needed to achieve the desired injector charge/bunch and stored current in the storage ring

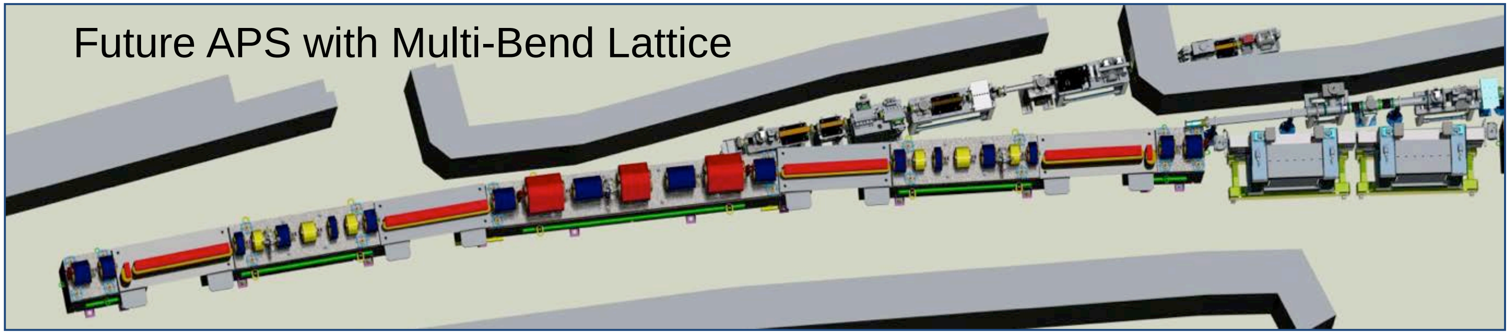
APS-Upgrade Description

- The APS-Upgrade is a next-generation synchrotron light source optimized for extreme brightness for hard x-rays
- 6 GeV, 200 mA, swap-out injection
  - A bunch will be dumped and a new bunch injected when the bunch falls to 90% of its initial charge
- Storage ring circumference 1104 m
- Multi-bend achromat (7-bend) lattice
- High brightness, ultra-low emittance (ε_x = 50-70 pm, ε_y = 7-50 pm)
- Incorporates a "timing mode" that uses 48 equally-spaced bunches of relatively high bunch charge (nominally 16 nC/bunch) – beam lifetime 1.8 hrs (10th-percentile lifetime)
- There will also be a "brightness mode" with 324 bunches and smaller vertical beam size and emittance – beam lifetime 8-10 hrs (10th-percentile lifetime)
- Dark time goal is 12 months, including commissioning and with-beam testing
- Critical Decision - 1 Review for the MBA lattice will be in September 2015

Present vs. Proposed Storage Ring

- Multi-bend achromat lattice enables a 50-fold reduction in horizontal emittance





$$\varepsilon_x = C_L \frac{E^2}{N_D^3}$$

E = Beam energy (E = 6 GeV for APS MBA)
N_d = Number of dipoles per sector (N_d = 7 for APS MBA)

Radiation Dose Limits

US limit for radiation workers	50 mSv/yr
Design of new or significantly modified facilities	10 mSv/yr
Argonne design goal for new/modified facilities	5 mSv/yr
APS – maximum rad worker dose	5 mSv/yr
APS – average rad worker dose	2 mSv/yr
Non-rad workers and general public	1 mSv/yr

- Surveys performed during APS operating history have demonstrated that the average dose to radiation workers is under 1 mSv/yr
- APS users are not considered to be radiation workers
- Area dosimeters in the experimental hall register less than the detection threshold

Definitions

Accelerator Safety Envelope (ASE)

- Defines the physical and administrative bounding conditions and controls for safe operations, based on the safety analysis in the facility Safety Assessment Document
- Separate ASEs exist for each part of the APS facility
  - Synchrotron – 308 W (e.g. 2 pps x 20 nC/pulse x 7.7 GeV)
  - Storage ring – 9280 J (e.g. 360 mA, 7 GeV or 327 mA, 7.7 GeV)
- The Accelerator Safety Envelope will not change with the APS-U

Design Performance Goal

- A set of parameters that describe the expected operating conditions of the facility
- For the present APS these are:
  - Synchrotron – 84 W (e.g. 2 pps x 6 nC/pulse x 7 GeV)
  - Storage ring – 2578 J (100 mA, 7 GeV)
- For the APS-U these would be:
  - Synchrotron – 120 W (e.g. 1 pps x 20 nC/pulse x 6 GeV)
  - Storage ring – 4420 J (200 mA, 6 GeV)

Potential Radiation Physics Issues

- High-charge injection
- Injected beam losses around injection septum (and other localized loss points)
  - Since injection will occur more frequently, there might be higher beam losses and thus higher average dose rates around the injection septum
- Stored beam losses
  - Higher stored energy and shorter lifetime will increase this source term
- Gas bremsstrahlung
  - Depends on residual gas composition and vacuum levels in ID straight sections
- Dose rate around beam dump for swap-out bunches

- The existing shielding design was based on the Accelerator Safety Envelope for each part of the APS
- While the safety envelope will not change, the source terms and dose rates will change for some situations
- The source terms for neutrons and photons must be well known to calculate dose rates accurately

Source Terms

- We are re-assessing the photon and neutron source terms due to electron interactions to more accurately determine dose rates
- The original shielding design for APS was based on empirical equations for the dose rate due to photons (bremsstrahlung) and neutrons and exponential attenuation

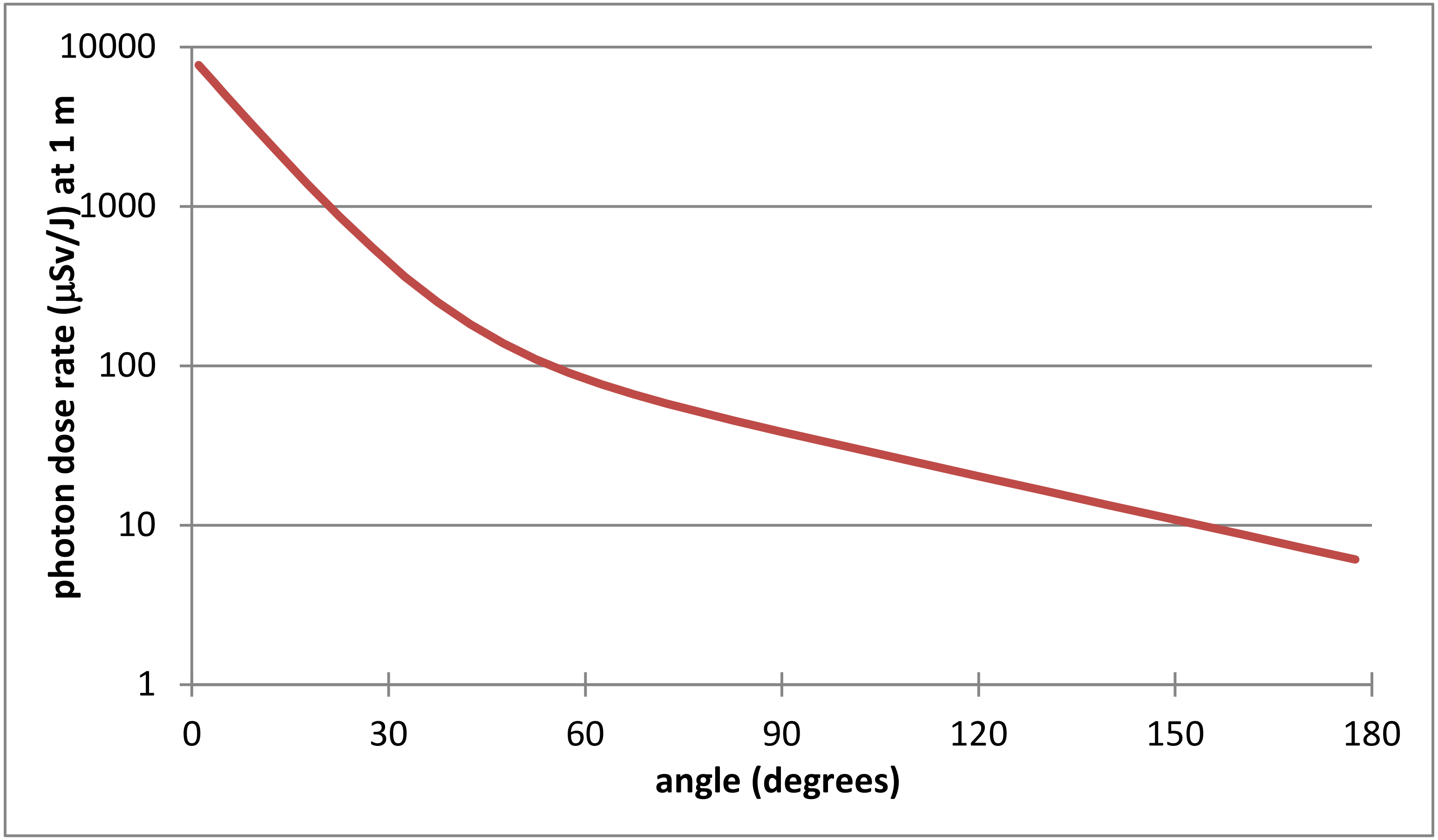
- Dose rate (μSv/J) due to bremsstrahlung given by

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

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

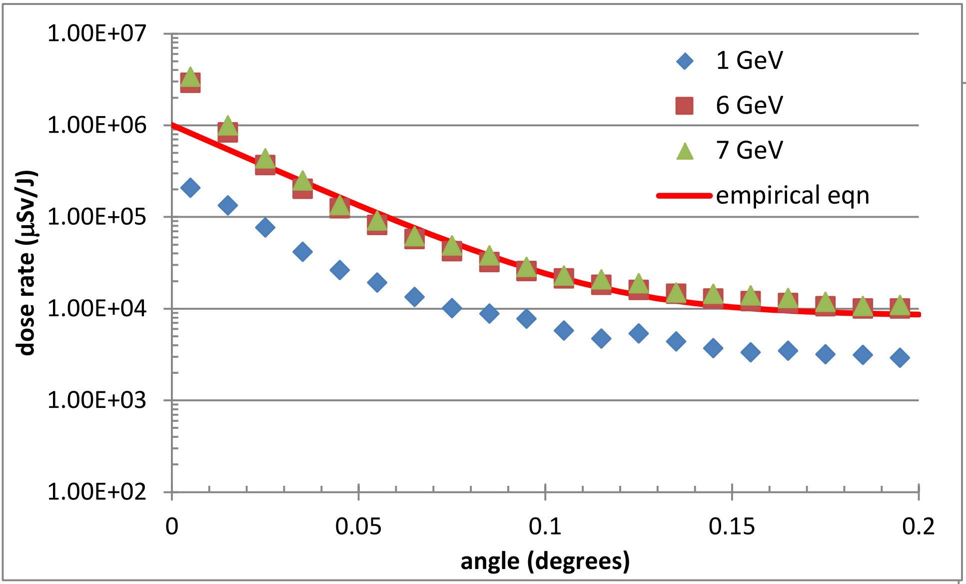
Bremsstrahlung Source Term

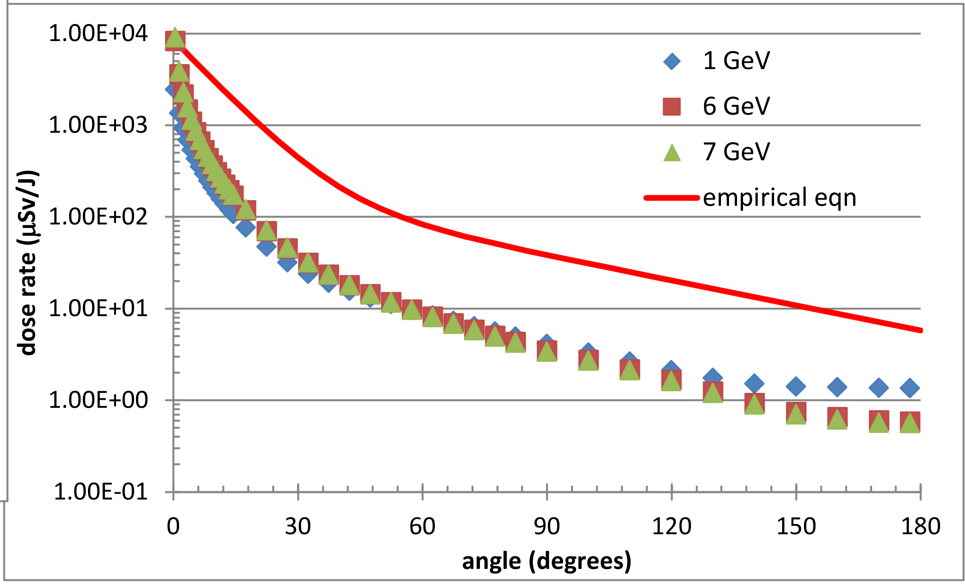
- The equation represents the case of a thick high-Z target
- The highly-peaked dose rate around 0° is not shown in the figure



Calculated Bremsstrahlung Source Term

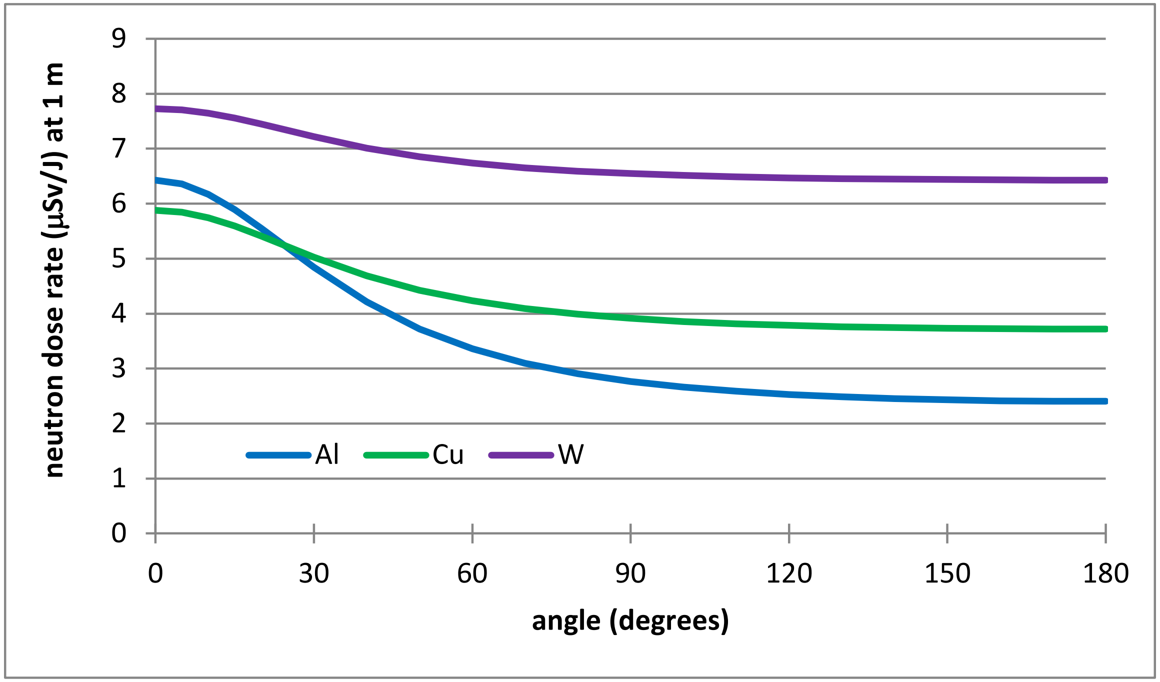
- MCNP6 was used to calculate the photons emitted due to electrons incident on the end of a copper cylinder 14 cm long x 10 cm diameter
- The empirical equation matches the dose rates calculated with MCNP6 well for the very forward angles, but is a factor of 10 too high at 90 degrees
- The source term at 90 degrees (to the incident electron beam) has the largest contribution to the dose rate outside the storage ring shielding





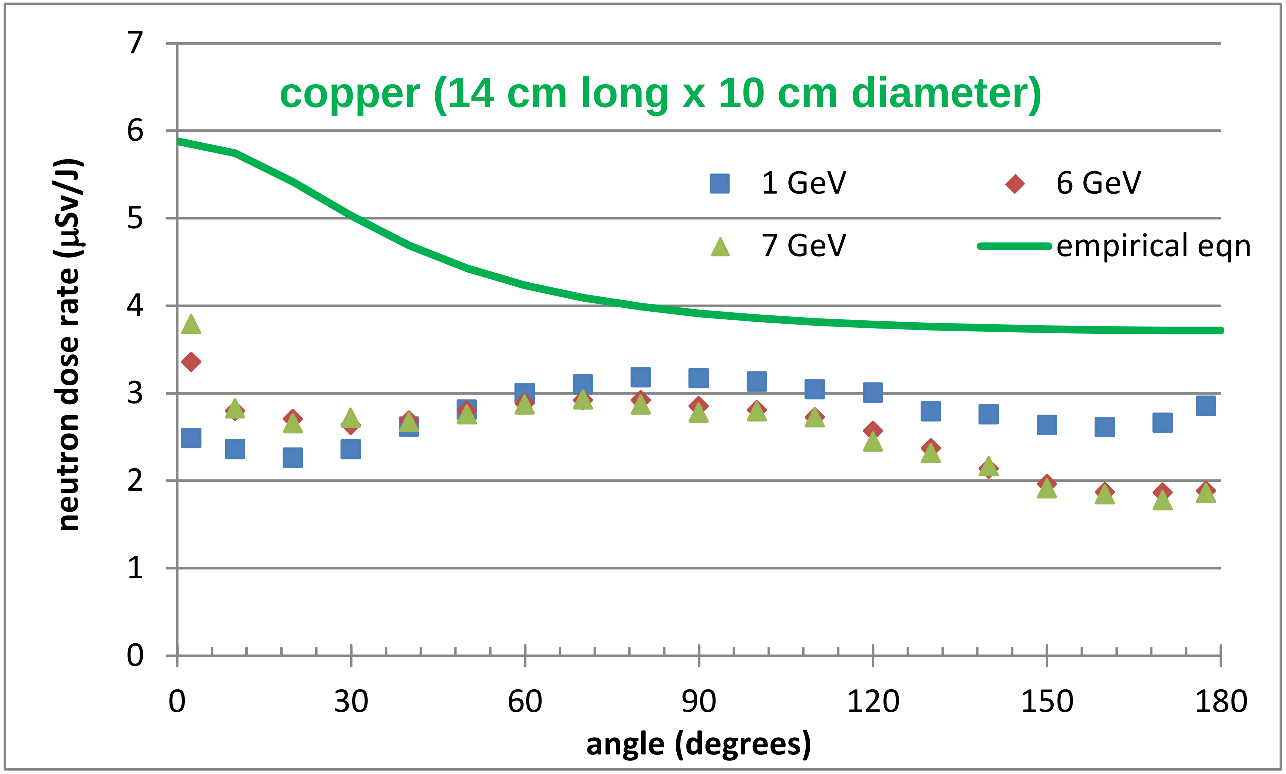
Neutron Source Term

- The empirical equation for the (unshielded) neutron dose rate has three components, each with its own angular distribution and Z dependence
  - Giant resonance neutrons (isotropic, increases with Z)
  - Medium-energy neutrons (forward peaked, decreases with Z)
  - High-energy neutrons (forward peaked, decreases with Z)
- These dose rates are based on neutron yields for semi-infinite materials, and perhaps correspond to production rather than the number of neutrons that escape



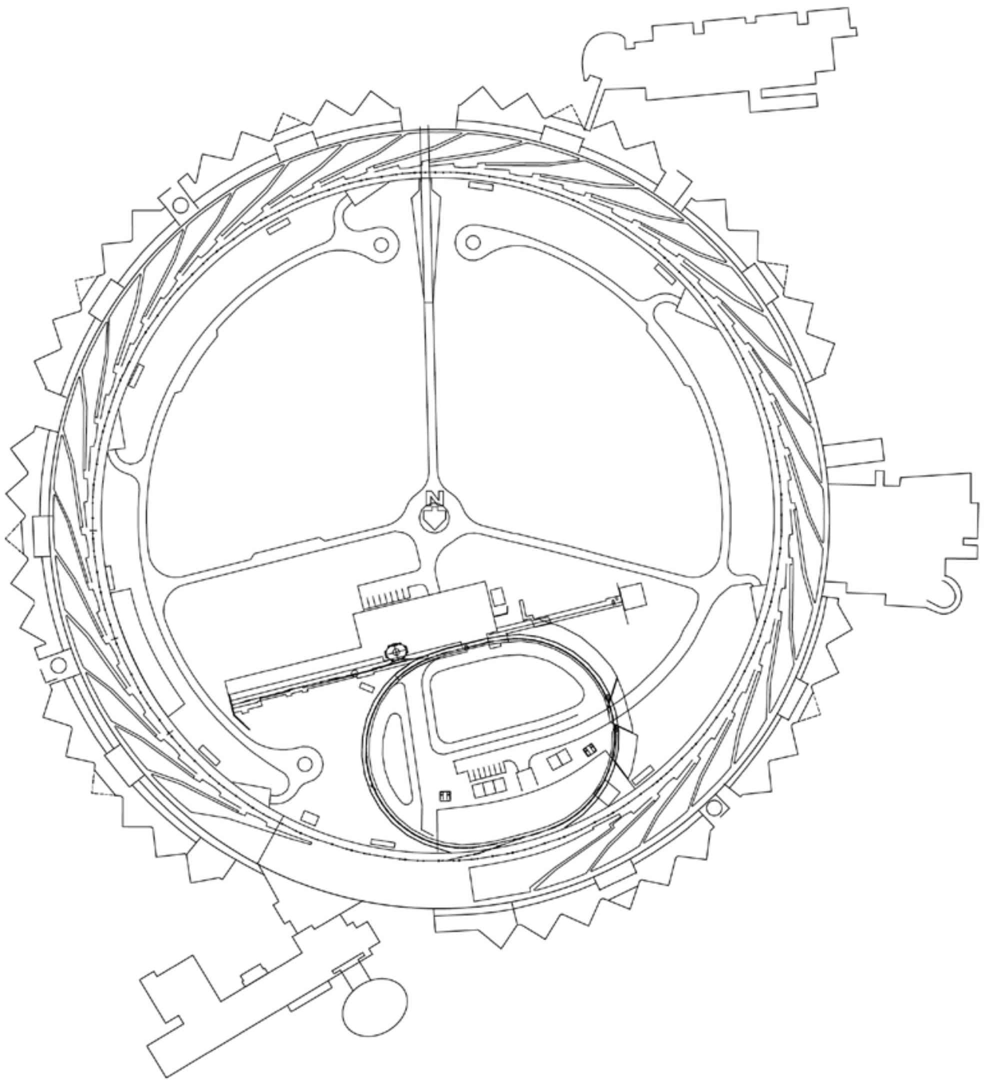
Calculated Neutron Source Term

- The neutron source term calculated with MCNP6 agrees with the equation within a factor of two
- The neutron source term varies more with the cylinder dimensions than does the photon source term
- There is also variation with incident electron energy
- Neutrons are the largest contributor to dose outside the shielding



High-Charge Injection

- Where are the loss points for charge when injecting high-charge bunches?
- What are the implications for the present bulk and local shielding?
- We are working closely with the accelerator physics group to determine the relevant source terms



Injected Beam Losses

Present APS

- Calculations for existing shielding assumed that the synchrotron is operating at the conditions of the ASE and injecting continuously into the storage ring
- 20% of injected power is assumed to be lost at the injection septum, with 20% of the remaining beam lost at the first insertion device (ID)
- Dose rates at all points are calculated to be below 2.5 µSv/hr assuming that the injection duty factor is 10%; for present operations this factor is much smaller

- At the design performance parameters, the injected power in the present system is 84 W (2 pps x 6 nC/bunch x 7 GeV)
- Only two locations could have doses above 2.5 µSv/hr at an injection duty factor of 100%; at 10% duty factor, all locations have dose rates below that value

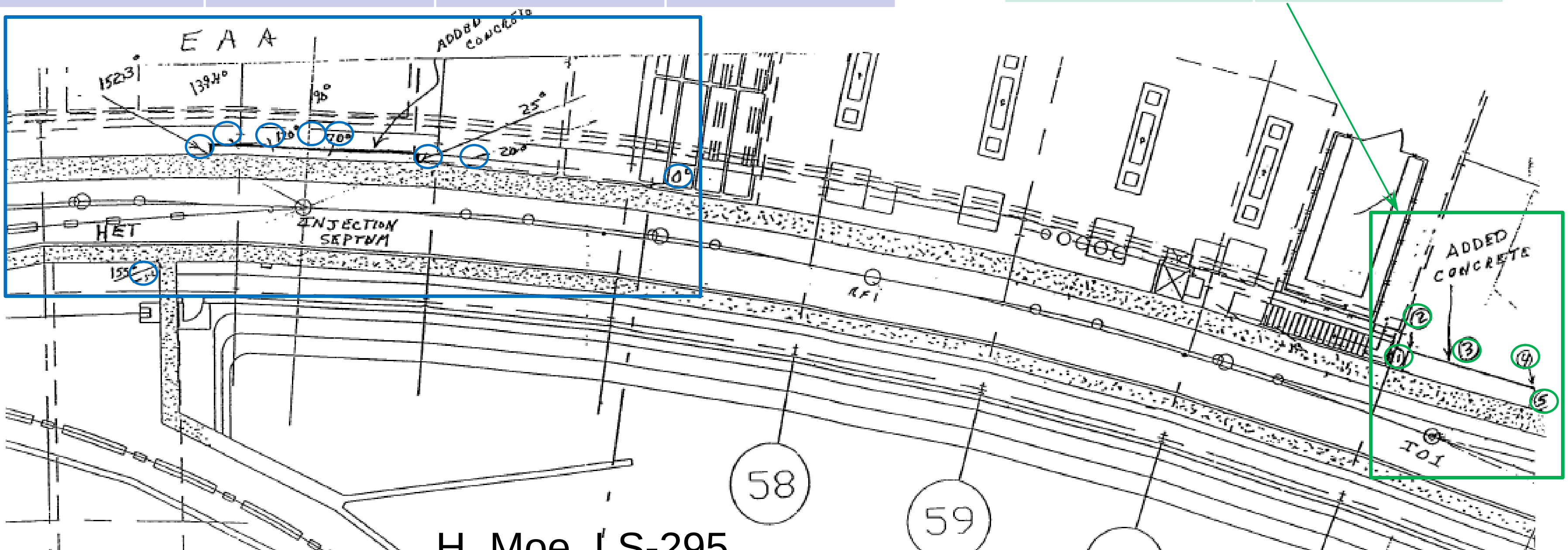
Injected Beam Losses (at 308 W injected power)

Loss at injection septum (mrem/hr)

location	dose rate	location	dose rate
0°	0.08	90° (side)	0.87
20°	0.32	90° (roof)	2.13
25°	1.35	120°	0.20
32.4°	0.90	139.4°	0.33
70°	0.82	152.3°	0.27

Loss near 1-ID (mrem/hr)

location	dose rate
1	6.1
2	0.13
3	0.77
4	0.01
5	7.1

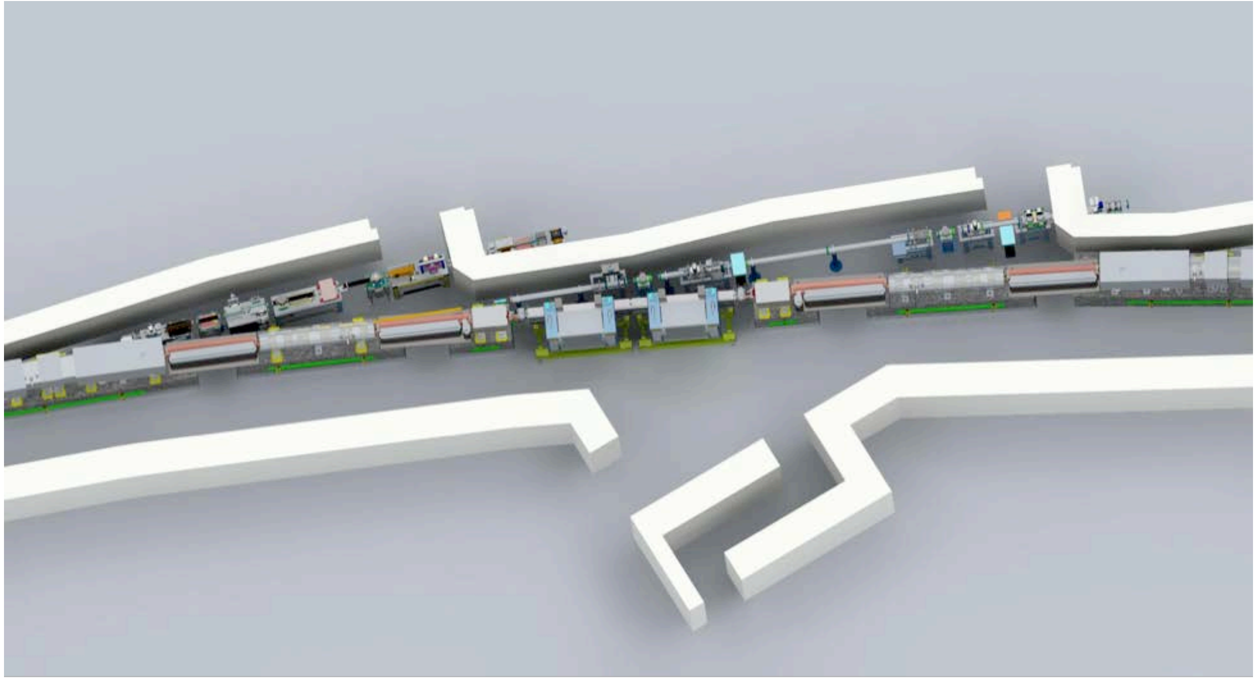


H. Moe, LS-295

Injected Beam Losses

APS Upgrade

- APS-U has the same safety envelope, so maximum dose rates will be unchanged
- The fraction of beam lost at injection is expected to be much less than 20%
- The injection duty factor, based on a beam lifetime of 1.8 hrs in the high-bunch-charge mode (a bunch is replaced when it falls to 90% of initial charge), is 7%
- The APS-U design performance will be 1 pps x 20 nC/bunch x 6 GeV = 120 W
- Since this is about the same as the current design performance of 84 W, the dose rates due to loss of injected beam are not expected to increase much



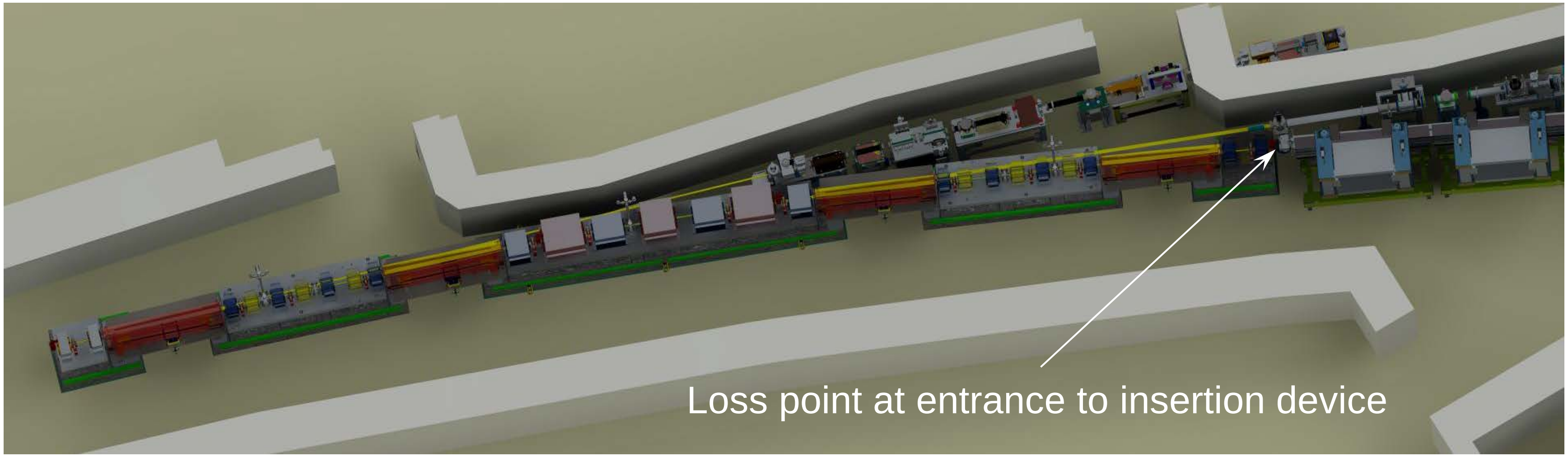
Stored Beam Losses – Uniform Losses

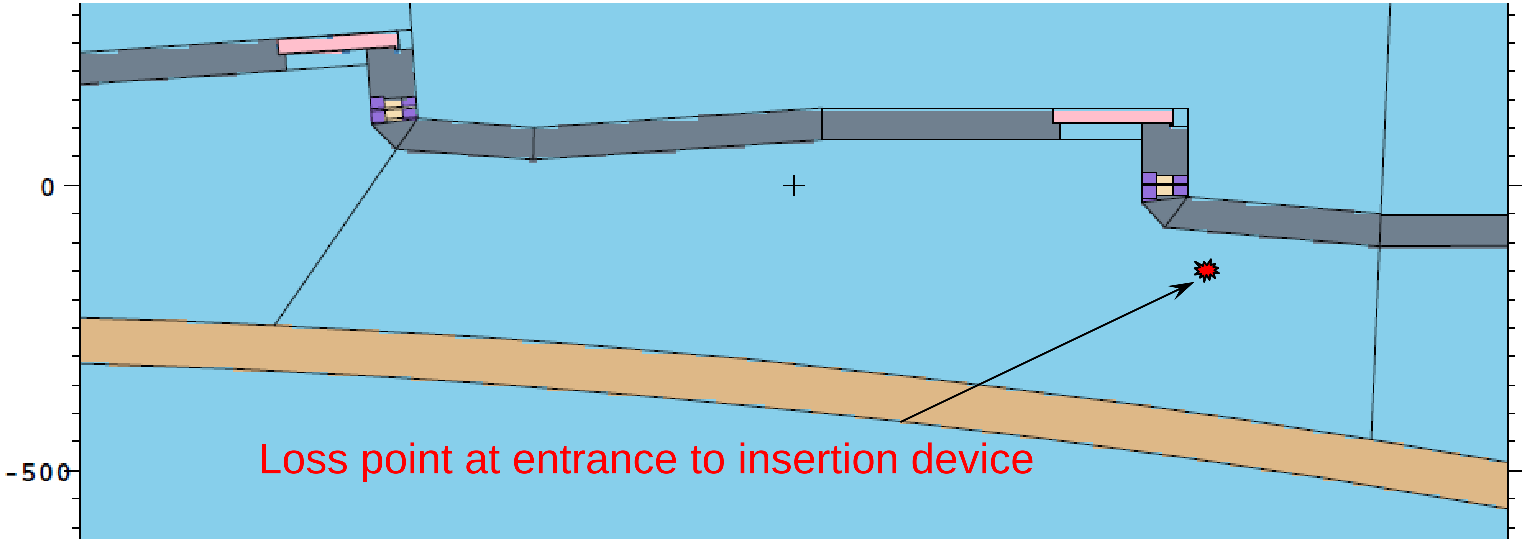
- The dose rate outside the shield wall depends on the stored beam energy and the beam lifetime
- The APS safety envelope has 9280 J stored energy in the storage ring (360 mA, 7 GeV or 324 mA, 7.7 GeV)
- Dose rate calculations for the present APS used empirical equations for the source terms, and treated shielding by exponential attenuation
- Dose rate calculations for the APS-Upgrade used source terms derived from MCNP6 calculations of 6 GeV electrons incident on copper
- Results do not include shielding due to accelerator components

Case	stored energy (J)	beam lifetime (hr)	dose rate (μSv/hr)
Present APS	9280	8	0.3
	2578	8	0.08
APS Upgrade	9280	1.8	0.49
	9280	8	0.11
	4420	1.8	0.23
	4420	8	0.05

Stored Beam Losses – Localized Losses

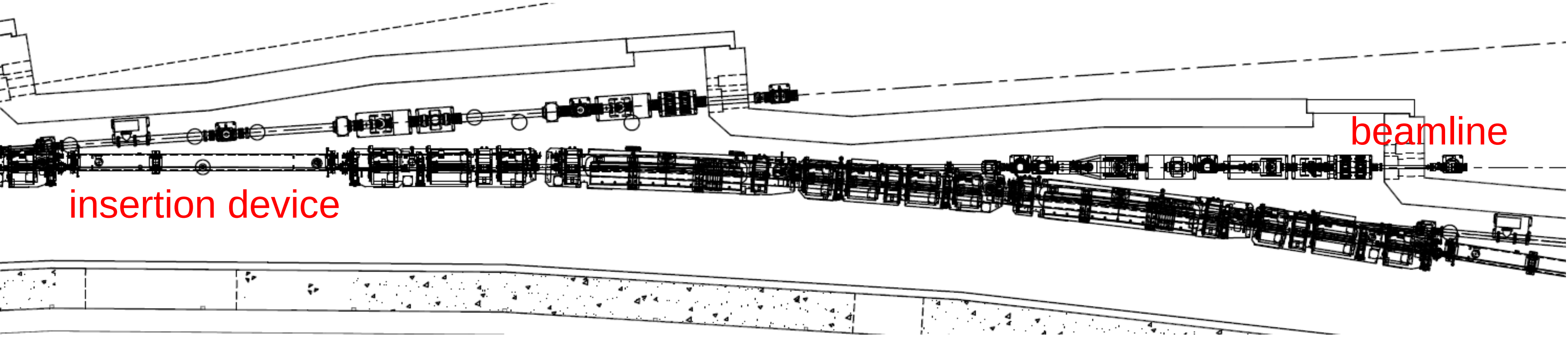
- MCNP6 will be used to calculate dose rates outside the shield wall
- Beam dynamics simulations are being performed to determine the loss points





Gas Bremsstrahlung

- The collision of electrons with the residual gas in the straight section of an insertion device is a significant source of bremsstrahlung



- Radiation yield depends on the pressure and composition of the residual gas
- The present storage ring has a nominal vacuum of 1 nT
- The design goal for the APS-U storage ring is 2 nT
- The ID straight sections in the Upgrade will be a factor of two shorter
- Some studies indicate that the residual gas in the APS-U will have significant quantities of CO and CO_2, rather than the H_2 that dominates the present storage ring
- We know the issues and will conduct detailed analyses to evaluate the potential problems

Swap-Out Mode Beam Dump

- In planned swap-out mode, entire 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 (bremsstrahlung, neutrons)
- Assuming a beam lifetime of 1.8 hrs, a bunch will drop to 90% of its initial charge after about 680 seconds
- For the stored beam parameters of the safety envelope, the beam dump would receive a time-average of 12.2 W of electrons (9280 J x 0.9 / 680 s)
- The location and shielding of this beam dump should be chosen consistent with ALARA considerations

Summary

- The proposed APS-U will have different operating parameters from the present system (lower energy, increased stored charge, increased injected charge/bunch, shorter beam lifetime)
- The Accelerator Safety Envelope will remain unchanged
- We have identified the major concerns for radiation doses in the APS-U
  - High-charge injection
  - Injected beam losses
  - Stored beam losses
  - Gas bremsstrahlung from ID straight sections
  - Swap-out beam secondary radiation
- Comparison to calculations for the existing storage ring suggests that some of the source terms may be increased, but by less than an order of magnitude
- Accurate determination of the source terms for all secondary radiations is needed
- Calculations for existing shielding were conservative (e.g., conservative source terms, shielding due to accelerator components was neglected)
- Monte Carlo simulations will be combined with empirical calculations to determine the effectiveness of the existing bulk and local shielding
- Supplemental shielding will be added as needed