Results from Studies of Thermomechanically-Induced Fatigue in GlidCop®

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Outline for the Presentation

• General discussion about fatigue

• Review existing design criteria limits for GlidCop® AL-15

• Progression of testing & analysis to establish new design criteria limits

• Mechanical testing of GlidCop® AL-15

• Thermomechanically-induced fatigue in GlidCop® AL-15 studies

• FE photon shutter transient non-linear FEA

• Proposed new design criteria limits for GlidCop® AL-15

• Using the thermal fatigue model as a tool to geometrically optimize component designs

• Built-in safety in the new design criteria limits

• Conclusions
General Discussion about Fatigue

**Low-Cycle Fatigue (LCF):**
- Is dominated by high amplitude low frequency plastic strains
- The elastic limit of the material is exceeded and permanent plastic deformation occurs
- Number of cycles to failure $< 10^4$

**High-Cycle Fatigue (HCF):**
- Is dominated by low amplitude high frequency elastic strains
- The elastic limit of the material is typically not exceeded
- Number of cycles to failure $10^4 – 10^6$ or more

**Our Situation:**
- For APS photon shutter operation we are in a region that involves both LCF and HCF
- The beam strike surface is in compression when the beam is present
- Most of the fatigue damage occurs from residual tension when the beam is turned off
- Fatigue damage on a beam strike surface is complicated because it involves tri-axial stress/strain
General Discussion about Fatigue

- Thermal fatigue ≠ Mechanical fatigue
- It is very hard to produce equivalent testing conditions
- Typically the slopes of the thermal and mechanical fatigue test results are similar

The general approach:  
1) Obtain temperature dependent mechanical fatigue data  
2) Perform thermal fatigue tests under actual operating conditions  
3) Use mechanical fatigue model as a base to develop a thermal fatigue model based on observed damage from the thermal fatigue tests
Existing APS GlidCop® Design Limits

The APS has used conservative criteria for establishing the maximum thermal load acceptable for X-ray beam-intercepting components:

1. The maximum temperature on GlidCop® surfaces shall not exceed 300°C in order to avoid material creep.
2. The maximum temperature on the cooling wall shall not locally exceed the water boiling temperature, and thus only single-phase water is allowed.
3. The maximum von Mises stress for photon shutters shall not exceed 400 MPa, the room temperature yield stress of plate stock GlidCop® Al-15.

SPring-8 also uses $T_{\text{max}} < 300^\circ\text{C}$ on GlidCop® surfaces for their design criteria

Numerous studies have been performed in the synchrotron community to assess the thermal fatigue life of GlidCop®:

1. Study at the ESRF in collaboration with APS: 2005
4. Study at SPring-8: 2006-2008
5. Study at the APS, Phase III Testing (this study): 2011-2014
Progression of Testing & Analysis to Establish New Design Criteria Limits

- Obtain temperature-dependent uniaxial mechanical fatigue data for GlidCop® AL-15
- Perform thermomechanically-induced fatigue tests on numerous GlidCop® AL-15 samples at S29 beamline at various power loading conditions
- Derive temperature-dependent mechanical fatigue model from data
- Perform transient non-linear analysis on all test samples to determine total strain range and peak temperature
- Transform mechanical fatigue model into thermal fatigue model by matching observed damage with life cycle predictions based on mean temperature
- Perform transient non-linear analysis on all FE absorbers under present and MBA Upgrade conditions
- Perform metallurgical analysis on all test samples to assess surface conditions and crack presence / geometry
- Define “failure” based on thermal fatigue model predictions and observed damage to samples
- Apply results to thermal fatigue model to assess life cycle predictions for each FE absorber case
- Propose new design criteria for GlidCop® AL-15 based on thermal fatigue as it applies to FE absorber analysis results. Explore how the criteria can be used to geometrically optimize component designs
Mechanical Testing of GlidCop® AL-15: True Stress vs. True Strain

- All tests were performed by Westmoreland Mechanical Testing & Research, Inc.
- Tension tests were performed in accordance with ASTM E21-09
- Compression tests were performed in accordance with ASTM E209-89a (2000)
- Seven different test temperatures were used
- Three samples were tested at each condition
- All samples were tested in pure argon gas (tests in vacuum were not available)

- True stress vs. true strain data are similar in tension and compression up to ~300°C
- All ANSYS transient non-linear simulations for this project use this data
Mechanical Testing of GlidCop® AL-15: Uniaxial Mechanical Fatigue Testing

- All tests were performed by Westmoreland Mechanical Testing & Research, Inc.
- Uniaxial mechanical fatigue tests were performed in accordance with ASTM E606-12
- Samples were machined from 1/2” x 6 3/8” GlidCop® AL-15 LOX extruded flats
- Four different test temperatures were used
- A total of 45 samples were tested
- All samples were tested in pure argon gas (tests in vacuum were not available)

Note: All Samples Tested in Pure Argon gas Environment

Advanced Photon Source, Argonne National Laboratory
Data Reduction for Uniaxial Mechanical Fatigue Tests

The Manson-Coffin equation and Basquin’s law are used to reduce the data set

\[ \frac{\Delta \varepsilon}{2} = \frac{\sigma_f}{E} (2N_f)^b + \varepsilon_f' (2N_f)^c \]

The following parameters are defined

- \( E \) the elastic modulus (Young's Modulus)
- \( K' \) the strain hardening coefficient
- \( n' \) the strain hardening exponent
- \( b \) the fatigue strength exponent (Basquin's exponent)
- \( \sigma_f' \) the fatigue strength coefficient
- \( c \) the fatigue ductility exponent (the Coffin-Manson exponent)
- \( \varepsilon_f' \) the fatigue ductility coefficient

b = -.066

c = -.48
Data Reduction for Uniaxial Mechanical Fatigue Tests

→ We can now solve for the Fatigue Strength Coefficient/Elastic Modulus and the Fatigue Ductility Coefficient

![Graph showing fatigue strength coefficient and elastic modulus vs. temperature](image)

For GlidCop AL-15 at Various Temperatures

- $\sigma_f = 1.1E+5 - 100T$
- $E = 1.9E+7 - 10000T$

The Mechanical Fatigue Model for GlidCop® AL-15:

$$\frac{\Delta \varepsilon_t}{2} = \left(0.67 - \frac{T}{2000}\right)(2N_f)^{-0.66} + \left(2.0 + \frac{3900}{T}\right)(2N_f)^{-0.48}$$

where:

- $\Delta \varepsilon_t$ = Total Strain Range (%)
- $T$ = Sample Temperature (K)
- $N_f$ = Number of Cycles to Failure
Data Reduction for Uniaxial Mechanical Fatigue Tests

For GlidCop AL-15 at Various Temperatures

\[ \Delta \varepsilon_t / 2 = \left( \frac{.67 - T / 2000}{2N_f} \right)^{-0.66} + \left( \frac{2 + 3900 / T}{2N_f} \right)^{-0.48} \]

Note: All Samples Tested in Pure Argon gas Environment
Thermomechanically-Induced Fatigue in GlidCop® Studies: Thermal Fatigue Model

• The mechanical fatigue model is transformed into a thermal fatigue model by redefining the temperature variable in the mechanical fatigue model as suggested by Taira (1973)
• The mean temperature between the maximum surface temperature and the cooling water temperature is used in the thermal fatigue model
• The thermal fatigue model is then used to predict the number of cycles to failure for each test sample
• Matching the observed surface damage on the samples with the thermal fatigue model prediction at 10,000 cycles defines “failure”

Thermal Fatigue Model:

\[
\frac{\Delta \varepsilon_t}{2} = \left(0.67 - \frac{T_m}{2000}\right)(2N_f)^{-0.066} + \left(2.0 + \frac{3900}{T_m}\right)(2N_f)^{-0.48}
\]

where:

- \( \Delta \varepsilon_t \) = Total Strain Range (%)
- \( T_m \) = Mean Temperature (K) = average of \( T_{\text{max}} \) & \( T_{\text{water}} \)
- \( N_f \) = Number of Cycles to Failure

A Note About Conducting Tests in a Pure Argon Gas Environment

- Takahashi from SPring-8 conducted a similar study in 2006-2008
- He noted the influence of the environment (air vs. vacuum) on the fatigue life

**Takahashi’s model:**

\[
\Delta \varepsilon_t = \Delta \varepsilon_p + \Delta \varepsilon_e = AN_f^{-\alpha} + BN_f^{-\beta},
\]

(1)

**Table 1**

Environment-dependent material properties of \( A, B, \alpha \) and \( \beta \) in equation (1). \( A \) and \( B \) are independently expressed as a function of temperature (\( T \)).

<table>
<thead>
<tr>
<th>Environment</th>
<th>( T ) (K)</th>
<th>Manson–Coffin ( A )</th>
<th>( -\alpha )</th>
<th>Basquin ( B )</th>
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</table>

**Our model:**

\[
\frac{\Delta \varepsilon_t}{2} = \left( 0.67 - \frac{T}{2000} \right) (2N_f)^{-0.66} + \left( 2.0 + \frac{3900}{T} \right) (2N_f)^{-0.48}
\]

\rightarrow Testing in a pure argon gas environment yields similar results as testing in vacuum

Thermomechanically-Induced Fatigue in GlidCop® Studies: Experimental Set-up

- Experiments were conducted at S29 FOE using two in-line U33.0 undulators
- A total of 30 GlidCop® AL-15 samples were tested
- Samples were subjected to 10,000 thermal cycles at normal incidence
- Various beam power loading conditions were applied to the samples

Experimental Set-up
Thermomechanically-Induced Fatigue in GlidCop® Studies: Sample Fabrication

- The first set of samples were made of solid GlidCop® AL-15 LOX machined from 50-mm x 56-mm extruded bar stock
- The remaining samples used 1/2” x 6 3/8” GlidCop® AL-15 LOX extruded flats machined to a 5-mm plate thickness and explosion bonded to an OFHC copper base
- Each sample assembly contained 4 sample blocks brazed to a common copper cooling tube loop.
- The sample beam strike surfaces were machined to a surface finish of Ra ~ 16-µin

Dimensions are in inches
Thermomechanically-Induced Fatigue in GlidCop® Studies: Thermal Cycle Times

- Cyclic thermal loading was applied with 1.4-second heating and 9-second cooling
- The sample heating time is sufficient to achieve near steady-state total strain range
- Peak compressive stress is achieved in less than a tenth of a second

Near steady-state total strain range

Peak compressive stress in < 0.1 sec.
Thermomechanically-Induced Fatigue in GlidCop® Studies: Sample Test Conditions

- We discovered after testing a number of samples that the beam was offset by .53-mm H x 1.18-mm V. The beam was centered for all subsequent sample tests.
- Calorimetry measurements were performed for offset beam cases and centered beam cases.
- The beam location for each sample was accounted for during ANSYS modeling.

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<th>Peak Heat Flux (W/mm²)</th>
<th>Number of Applied Cycles</th>
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Beam offset .53mm H x 1.18mm V
Beam centered
Thermomechanically-Induced Fatigue in GlidCop® Studies: Sample Modeling

- Transient non-linear model simulations were performed using ANSYS for each sample test condition employing the multilinear kinematic hardening model
- SRUFF was used for all undulator power calculations
- True stress vs. true strain data were used in the simulations
- Temperature-dependent material properties were used in the simulations (thermal conductivity, specific heat, thermal expansion coefficient and Young’s modulus)
- The simulations yield the maximum temperature and total strain range data required to predict the fatigue life for each sample

Analysis for samples 20-24
Thermomechanically-Induced Fatigue in GlidCop® Studies: Sample Modeling

Note: The strain caused by the first heating cycle plastically deforms the material causing kinematic strain hardening to occur and this increases the yield stress.

Analysis for samples 20-24
Thermomechanically-Induced Fatigue in GlidCop® Studies: Metallurgical Analysis

- Test samples were metallurgically examined in-house for surface damage and crack presence/geometry

Figure 1: GlidCop® responds in a progressive predictable manner to increasing X-ray power loads.
Thermomechanically-Induced Fatigue in GlidCop® Studies: Metallurgical Analysis

- After surface images were acquired, samples were cut, polished, etched and examined in sections to obtain information on crack morphology.

**What is a ‘Crack’, a ‘Cat Scratch’ and a ‘Surface Heave’?**

**Cracks** in GlidCop® are fascinating sinuous paths, always following grain boundaries, growing by fatigue processes from the surface down into the bulk metal.

It took 10,000 cycles of double undulator radiation at a 19.7mm gap, almost 1400 W of total power per cycle, to grow this crack in 30 hours.

**Surface Heaving** in GlidCop® is the result of high power being deposited on a surface constrained on all sides. The metal plastically deforms upward and folds, much like mountain building tectonics on earth. Note the folding and bending of the underlying planar grain structure in the heave. [Matches blue box of Figure 1]

**‘Cat Scratches’** are shallow regions of surface grain drop-out. They always have rounded ‘V-like’ shapes and are the result of surface thermal compression ejecting weakly bound grains.

This surface has a 283 µm deep crack (right) and a 7.44 µm ‘cat scratch’ (left & magnified). [Matches green box of Figure 1]
Thermomechanically-Induced Fatigue in GlidCop® Studies: Metallurgical Analysis

Evolution of GlidCop® Crack Morphology

**Figure 2: GlidCop® crack profiles**
Thermomechanically-Induced Fatigue in GlidCop® Studies: Sample Data Base

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Total Absorbed Power (W)</th>
<th>Peak Flux (W/mm²)</th>
<th>Total Strain Range (%)</th>
<th>Maximum Temperature, 1.4s heating (K)</th>
<th>Mean Temperature (K)</th>
<th>Largest Crack Length (µm)</th>
<th>Largest Crack Width (µm)</th>
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<td>1034</td>
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<td>320.0</td>
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<td>666</td>
<td>4792</td>
<td>34.4</td>
<td>320.0</td>
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</tr>
</tbody>
</table>

→ “Failure” yields “cat scratches” with the possibility of small shallow cracks < 2 mm in length
“Cat Scratches” are shallow regions of surface grain drop-out. They always have rounded “V-like” shapes and are the result of surface thermal compression ejecting weakly bound grains. Since the material is extruded, the copper grains are long and thin with dimensions on the order of several microns in depth/width and tens to hundreds of microns in length.

→ “Failure” yields “cat scratches” with the possibility of small shallow cracks < 2 mm in length
Thermomechanically-Induced Fatigue in GlidCop® Studies: “Failure” Zone

1. No surface degradation
   \(N_f = 18,100\)

2. "Cat scratches", 1 small shallow crack
   \(N_f = 17,300\)

3. "Cat scratches", some small shallow cracks
   \(N_f = 7,650\)

4. "Cat scratches", 1 small shallow crack
   \(N_f = 7,220\)
FE Photon Shutter Transient Non-Linear Analysis

- Transient non-linear analyses were performed on the APS FE photon shutter designs in operation including V1.2 P2-20, V1.5 P2-30, PS2 HHL shutter and PS2 CU shutter

- Both the existing maximum design conditions and the maximum MBA lattice baseline conditions were considered

- True stress vs. strain data and temperature-dependent material properties were used in the simulations

- A 10-sec. heating and 40-sec. cooling cycle time was used, sufficient to achieve near steady-state total strain range

- For each transient simulation, a steady-state thermal simulation was performed first because the maximum steady-state temperature is used in the thermal fatigue model

- The simulations yield the maximum temperature and total strain range data required to predict the fatigue life for each shutter case
FE Photon Shutter Transient Non-Linear Analysis

V1.2 P2-20

PS2 HHL Shutter

V1.5 P2-30

PS2 CU Shutter

Advanced Photon Source, Argonne National Laboratory
FE Photon Shutter Transient Non-Linear Analysis

Plastic + Elastic

Elastic

Plastic

Elastic

Plastic

Elastic

Plastic

Elastic

Total strain range = 0.0089524
Elastic strain range = 0.0029404
Plastic strain range = 0

Total strain range = 0.002628
Elastic strain range = 0.002628
Plastic strain range = 0
## FE Photon Shutter Transient Non-Linear Analysis

<table>
<thead>
<tr>
<th>Photon Shutter Type</th>
<th>Operating Conditions</th>
<th>Source Parameters</th>
<th>Aperture Size at Shutter Location (mm x mm)</th>
<th>Total Power (W)</th>
<th>Peak Heat Flux (W/mm²)</th>
<th>Maximum Temperature (°C)</th>
<th>Maximum Cooling Wall Temperature (°C)</th>
<th>Mean Temperature (K)</th>
<th>Peak Compressive / Tensile Stress (Mpa)</th>
<th>Elastic Strain Range (%)</th>
<th>Plastic Strain Range (%)</th>
<th>Total Strain Range (%)</th>
<th>Estimated Number of Cycles to Failure</th>
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</thead>
<tbody>
<tr>
<td>V1.2 P2-20</td>
<td>Maximum Design Condition from TB-50</td>
<td>Single U33.0</td>
<td>9 x 6</td>
<td>6,776</td>
<td>18.0</td>
<td>314.6</td>
<td>147.1</td>
<td>443.0 (169.8°C)</td>
<td>-204.8 / 236.0</td>
<td>0.35786</td>
<td>0.06882</td>
<td>0.42668</td>
<td>152,000</td>
</tr>
<tr>
<td>V1.2 P2-20</td>
<td>Water Boiling @ 153°C Condition</td>
<td>Single U33.0</td>
<td>9 x 6</td>
<td>7,134</td>
<td>18.9</td>
<td>330.8</td>
<td>153.7</td>
<td>451.1 (177.9°C)</td>
<td>-211 / 250.3</td>
<td>0.36587</td>
<td>0.09170</td>
<td>0.45757</td>
<td>101,000</td>
</tr>
<tr>
<td>V1.5 P2-30</td>
<td>Maximum Design Condition from TB-50</td>
<td>Single U33.0</td>
<td>9 x 6</td>
<td>11,911</td>
<td>33.4</td>
<td>290.4</td>
<td>94.8</td>
<td>430.9 (157.7°C)</td>
<td>-210.5 / 246.9</td>
<td>0.36629</td>
<td>0.09583</td>
<td>0.46212</td>
<td>114,000</td>
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<tr>
<td>V1.5 P2-30</td>
<td>&gt; 20,000 Cycles to Failure Condition</td>
<td>Dual In-Line U27.5</td>
<td>13.48 x 5.52</td>
<td>25,062</td>
<td>36.4</td>
<td>393.4</td>
<td>121.2</td>
<td>482.4 (209.2°C)</td>
<td>-203.6 / 252.1</td>
<td>0.37296</td>
<td>0.10417</td>
<td>0.47713</td>
<td>53,500</td>
</tr>
<tr>
<td>PS2 HHL Shutter</td>
<td>Maximum Design Condition from HHL FE Design Report</td>
<td>Dual In-Line U33.0</td>
<td>5 x 6</td>
<td>14,600</td>
<td>24.5</td>
<td>248.2</td>
<td>91.9</td>
<td>409.8 (136.6°C)</td>
<td>-205.1 / 173.0</td>
<td>0.30881</td>
<td>0.00615</td>
<td>0.31496</td>
<td>9.57E+06</td>
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<tr>
<td>PS2 HHL Shutter</td>
<td>&gt; 20,000 Cycles to Failure Condition</td>
<td>Dual In-Line U27.5</td>
<td>5.6 x 6.72</td>
<td>25,527</td>
<td>32.4</td>
<td>375.3</td>
<td>133.3</td>
<td>473.2 (200°C)</td>
<td>-215.4 / 286.6</td>
<td>0.38103</td>
<td>0.17255</td>
<td>0.55358</td>
<td>20,800</td>
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<tr>
<td>PS2 Canted Undulator Shutter</td>
<td>Maximum Design Condition from MEDS02 Report</td>
<td>Dual Canted U33.0 with 1 mrad Beam Separation 200 mA</td>
<td>10 x 6</td>
<td>19,900</td>
<td>10.4</td>
<td>247.9</td>
<td>129.8</td>
<td>409.6 (136.5°)</td>
<td>-202.4 / 0.0</td>
<td>0.26528</td>
<td>0</td>
<td>0.26528</td>
<td>1.03E+08</td>
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<tr>
<td>PS2 Canted Undulator Shutter</td>
<td>Water Boiling @ 153°C Condition</td>
<td>Dual Canted U27.5 with 1 mrad Beam Separation 330 mA</td>
<td>5.6 x 6.72</td>
<td>20,445</td>
<td>15.9</td>
<td>331.5</td>
<td>153.8</td>
<td>451.4 (178.3°C)</td>
<td>-185.1 / 97.1</td>
<td>0.23395</td>
<td>0</td>
<td>0.23395</td>
<td>3.28E+08</td>
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</table>
Proposed New Design Criteria Limits for GlidCop® AL-15:

1. Components can be designed with a maximum surface temperature of 375°C or to where the cooling water will begin to boil; whichever occurs first will be the limiting criteria.

2. Components can be designed with a maximum surface temperature up to 405°C, the creep temperature for GlidCop® AL-15, if transient non-linear analysis is performed to ensure that the number of cycles to failure exceeds 20,000 cycles using the thermal fatigue model below:

\[ \Delta \varepsilon_t = \left(0.67 - \frac{T_m}{2000}\right)(2N_f)^{-0.66} + \left(2 + \frac{3900}{T_m}\right)(2N_f)^{-48} \]

where: \( \Delta \varepsilon_t = \text{Total Strain Range (\%)} \)
\( T_m = \text{Mean Temperature (K) = average of } T_{max} \text{ & } T_{water} \)
\( N_f = \text{Number of Cycles to Failure} \)

3. Components can be designed beyond the boiling point of the water if critical heat flux (CHF) analysis is performed to ensure that a dry-out condition can never be reached.

Note: A surface roughness of Ra ≤ 16 µin should be specified for the beam strike surface.

→ For most component designs, only steady-state thermal analysis will be required to verify that the design meets the design criteria limits. Stress analysis is not required when the maximum surface temperature ≤ 375°C.

→ The thermal fatigue model provides a tool that can be used to geometrically optimize component designs.
Using the Thermal Fatigue Model as an Optimizing Tool for Component Designs

- The thermal fatigue model can be used to geometrically optimize component designs
- Parameters such as cooling wall thickness, grazing incidence angle, cooling channel layout, etc. can be optimized through parametric study using the thermal fatigue model

### Varying Grazing Incidence Angle for PS2 HHL Shutter with Fixed Cooling Wall Thickness = 9-mm:

<table>
<thead>
<tr>
<th>Photon Shutter Type</th>
<th>Operating Conditions</th>
<th>Source Parameters</th>
<th>Grazing Incidence Angle (degrees)</th>
<th>Shutter Length (mm)</th>
<th>Total Power (W)</th>
<th>Peak Heat Flux (W/mm²)</th>
<th>Maximum Temperature (°C)</th>
<th>Maximum Cooling Wall Temperature (°C)</th>
<th>Mean Temperature (°C)</th>
<th>Peak Stress (Mpa)</th>
<th>Elastic Strain Range (%)</th>
<th>Plastic Strain Range (%)</th>
<th>Total Strain Range (%)</th>
<th>Estimated Number of Cycles to Failure</th>
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</thead>
<tbody>
<tr>
<td>PS2 HHL Shutter</td>
<td>M&amp;O Lattice Baseline Condition</td>
<td>Dual In-Line U27.5 200 mA</td>
<td>1.05</td>
<td>647.7</td>
<td>13,062</td>
<td>16.5</td>
<td>199.3</td>
<td>80.4</td>
<td>385.3 (112.2°)</td>
<td>196.9 / 117.5</td>
<td>0.25698</td>
<td>0</td>
<td>0.25698</td>
<td>2.38×10⁸</td>
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<tr>
<td>PS2 HHL Shutter</td>
<td>M&amp;O Lattice Baseline Condition</td>
<td>Dual In-Line U27.5 200 mA</td>
<td>1.5</td>
<td>556.0</td>
<td>13,063</td>
<td>23.63</td>
<td>276.5</td>
<td>103.1</td>
<td>424.0 (150.8°)</td>
<td>199.3 / 193.9</td>
<td>0.33136</td>
<td>0.01847</td>
<td>0.34982</td>
<td>390,000</td>
</tr>
<tr>
<td>PS2 HHL Shutter</td>
<td>M&amp;O Lattice Baseline Condition</td>
<td>Dual In-Line U27.5 200 mA</td>
<td>1.75</td>
<td>525.5</td>
<td>13,065</td>
<td>27.57</td>
<td>319.7</td>
<td>115.6</td>
<td>445.6 (172.4°)</td>
<td>198.6 / 236.3</td>
<td>0.3604</td>
<td>0.0736</td>
<td>0.4339</td>
<td>37,900</td>
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<tr>
<td>PS2 HHL Shutter</td>
<td>M&amp;O Lattice Baseline Condition</td>
<td>Dual In-Line U27.5 200 mA</td>
<td>2.08</td>
<td>496.4</td>
<td>13,069</td>
<td>32.77</td>
<td>376.5</td>
<td>131.7</td>
<td>473.9 (201.8°)</td>
<td>197.0 / 277.5</td>
<td>0.39184</td>
<td>0.14963</td>
<td>0.54167</td>
<td>25,900</td>
</tr>
</tbody>
</table>

The reduction in life cycle compared to the reduction in shutter length changes significantly between 1.5° and 1.75° and therefore the optimum grazing incidence angle lies between them
Built-In Safety in the Proposed New Design Criteria Limits

- Surface damage is cumulative (*Miner’s Rule*). Our thermal fatigue model assumes every thermal cycle will occur at the worst-case loading condition. In operation, a shutter will experience many load cycles much less than the worst-case loading condition.

  → We can expect many more cycles to “failure” than the thermal fatigue model predicts.

- Sample #47 was tested under the worst-case possible conditions we could achieve with two in-line U33.0 undulators operating at 100 mA with closed gaps at 11.0 mm. Even after 10,000 thermal cycles, the final crack length was < 10 mm and the maximum crack depth was < 2 mm.

  → It is hard to imagine a scenario where a crack could ever reach the cooling channel considering the surface temperature here was above the melting point.
Conclusions

• The new design criteria limits allows much higher operating limits compared to the old design criteria.

• For all of the APS photon shutter cases we have looked at, following the proposed new design criteria limits will yield 20,000 or more cycles to failure.

• For most component designs, only steady-state thermal analysis will be required to verify that the design meets the new design criteria limits. Stress analysis is not required when the maximum surface temperature $\leq 375^\circ C$.

• The thermal fatigue model provides a tool that can be used to geometrically optimize component designs.

• Based on the new design criteria limits, all of the existing photon shutter designs except for the V1.2 P2-20 could be used for the APS upgrade.

To evaluate the new design criteria limits, thermomechanically-induced fatigue tests, performed at grazing-incidence angle on a photon shutter installed in an ID front end, are being considered.
The following are slides not presented but may be of interest
Data Reduction for Uniaxial Mechanical Fatigue Tests

- The cyclic strain hardening relation can be found from the uniaxial mechanical fatigue data.
- The cyclic strain hardening exponent \( n \) is a measure of how a material hardens from applied strain.
- A value of \( n=0 \) → the material is a perfect plastic solid.
- A value of \( n=1 \) → the material is a 100% elastic solid.

\[
\sigma = K \Delta \varepsilon_p^n
\]

\( \sigma \) = Applied Stress (MPa)
\( \Delta \varepsilon_p \) = Resulting Plastic Strain (%)
\( K \) = Cyclic Strain Hardening Coefficient (MPa)
\( n \) = Cyclic Strain Hardening Exponent

In our case:

\[
\sigma = (730 - 0.64 T) \Delta \varepsilon_p^{0.10}
\]

→ GlidCop® AL-15 behaves very differently than copper.

<table>
<thead>
<tr>
<th>Material</th>
<th>( n )</th>
<th>( K ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-carbon steel (annealed)</td>
<td>0.21</td>
<td>600</td>
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<tr>
<td>4340 steel alloy (tempered @ 315°C)</td>
<td>0.12</td>
<td>2650</td>
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<tr>
<td>304 stainless steel (annealed)</td>
<td>0.44</td>
<td>1400</td>
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<tr>
<td>Copper (annealed)</td>
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<td>530</td>
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<tr>
<td>Naval brass (annealed)</td>
<td>0.21</td>
<td>565</td>
</tr>
<tr>
<td>2024 aluminum alloy (heat treated—T3)</td>
<td>0.17</td>
<td>780</td>
</tr>
<tr>
<td>AZ-31B magnesium alloy (annealed)</td>
<td>0.16</td>
<td>450</td>
</tr>
</tbody>
</table>

From Wikipedia
Can the Proposed New Design Criteria Limits be Applied to A Case with Very Small Beam Footprint Size?

Conditions:
- DCS pink beam conditions
- TFE sample, normal incidence
- 61.1 µm x 26.3 µm beam size
- 8.95 W total power
- Heat Flux = 5,570 W/mm²
- 0.05 sec. heating, 0.05 sec. cooling
- 375.5°C steady-state (374.2°C transient)

The proposed new design criteria limits work for a case with very small beam footprint size

\[ \varepsilon_T = 0.4106\% \]
\[ T_{\text{max}} = 375.5°C \]

\[ N_f = 205,500 \text{ cycles to failure} \]

→ The proposed new design criteria limits work for a case with very small beam footprint size
How Does a Thermal Bump Change the Grazing Incidence Angle?

The maximum thermal bump height is ~ 50 µm and the maximum angular change is ~ 0.07°.

The maximum angular change occurs well outside of the beam center, and the grazing incidence angle is unchanged at the beam center.