APS-U: Front Ends

High Heat Load Related Issues

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Acknowledgement

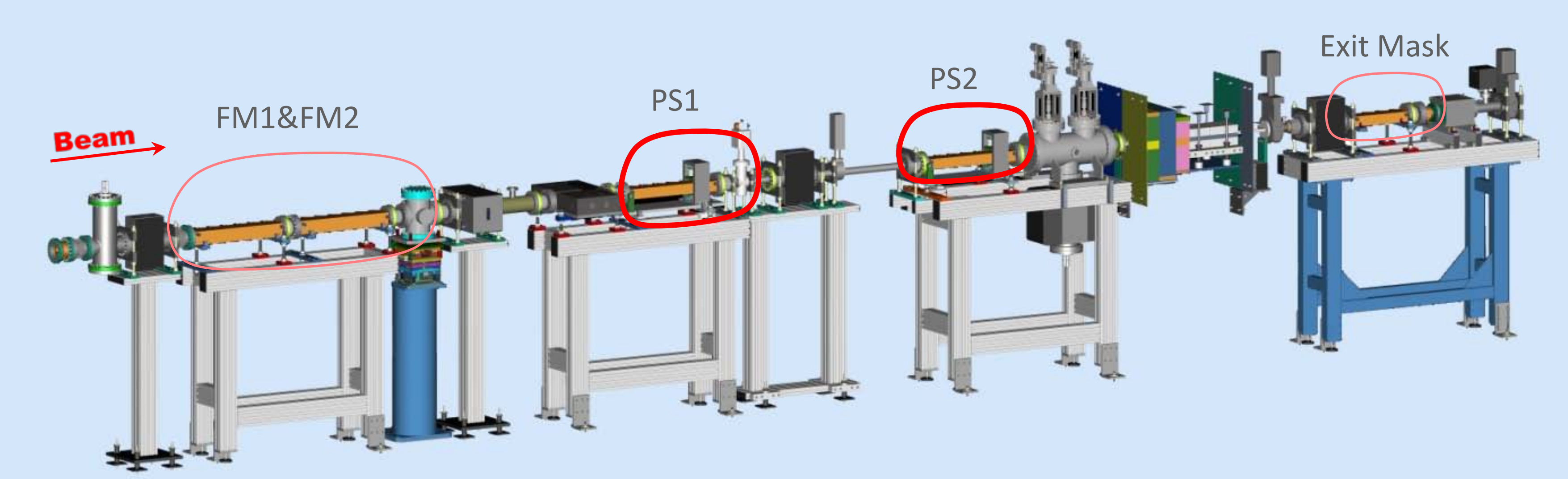
This talk is based on the effort and knowledge of many

- Deming Shu, who's pioneering work made many things possible
  - *Once the house is built it is easy to find better location for bedroom window – Serbian proverb*
- Yifei Jaski, who's truly remarkable HHL designs will remain building blocks of APS-U Front ends
- Jeff Collins, who's work let us use cooling techniques that are among the most efficient in the world
- Dana Capatina, she was the one that developed FEA models used in CHF related work
- Ali Khounsari, who's relentless scouting brought some very interesting ideas

Outline

- Introduction to Front ends
- Current Front-end operation environment and design criteria
- What kind of the environment do we expect after the upgrade?
- What are the possible challengess?
- How do we plan to deal with them?

Introduction to Front ends



Function of Front-ends

- Collimate the Bremsstrahlung
- Collimate the SR
  - Absorb power outside of the central cone
- Block SR and BR inside the storage ring to allow access in the FOE
  - Absorb the entire SR beam
  - Protect BR shutter
- Provide beam position information for steering adjustments
- Create buffer zone between SR and beamline vacuum

Components of the Front-ends intentionally exposed to the photon beams

- Fixed masks
  - Permanently exposed to the peripheral part of the beam
- Photon shutters (PS1 & PS2)
  - Intermittently exposed to the core of the beam
- Exit mask
  - Permanently exposed to the peripheral part of the beam

Current Front-end operation environment and design criteria

- Limited space
  - longitudinally and transversely
    - RSS requires redundant systems
- High x-ray power loads
  - Multi-kW total power
  - Extremely high power density
    - At the position of the PS1 a single UA produces a peak heat flux of 535 W/mm^2
    - Compare that to a heat flux at the photosphere of the sun:
      $q_{Sp} = \varepsilon\sigma T^4 = 63$ W/mm^2
  - The large and concentrated incident power produces high temperature gradients and high stresses
- Repeated thermal cycling

Design to prevent structural and cooling failures

- Conservative limits have always been used
- Maximum temperature on Glidcop surface < 300 °C to prevent creep
- Maximum temperature on cooling channel wall< water boiling temperature at the channel pressure to maintain single phase heat transfer
- Maximum stress < 400 MPa to avoid fatigue

No thermally induced failure to date!

Existing Front-end designs

V. 1.2

- Compatible with undulators and wigglers
- Hockey stick SR shutters
    - Beam intercepted on horizontal surface
    - 1.5 - 2 degree angle of incidence
    - 15 W/mm^2
    - Copper mesh in cooling channels for convective cooling enhancement
    - Cooling wall thickness = 6.5 mm
- Original 20 sectors

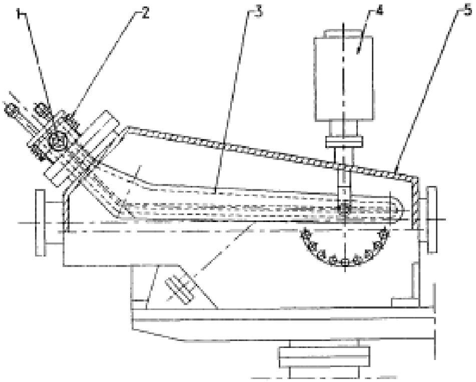
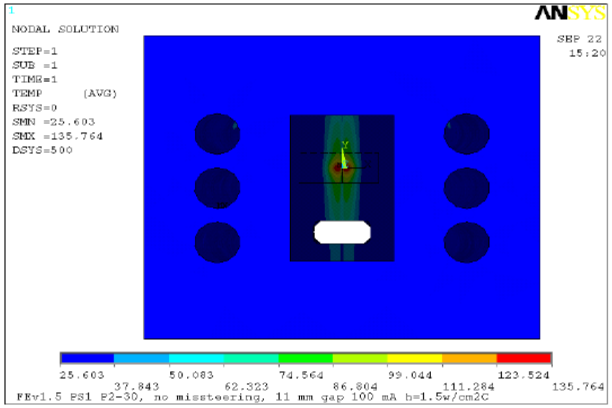


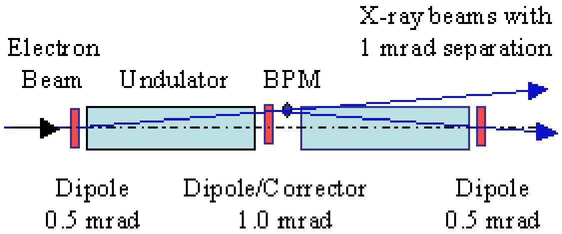
Fig. 6. First photon shutter for the APS ID front end: (1) hinging joint, (2) welded bellows, (3) "hockey-stick-type water-cooled blade, (4) actuator, (5) vacuum chamber.

V. 1.5

- Introduced a V-shaped photon shutters in a box-type explosively bonded structure
    - Beam intercepted on vertical surface
    - 1.68 degree incidence angle
    - 15 W/mm^2
    - Less expensive to fabricate
- Designed for undulators only
- Designed for 150 mA with one UA33
- Used in 4 sectors

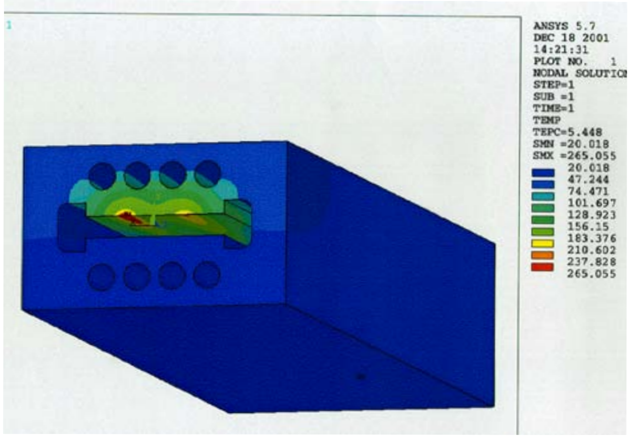


Existing Front-end designs



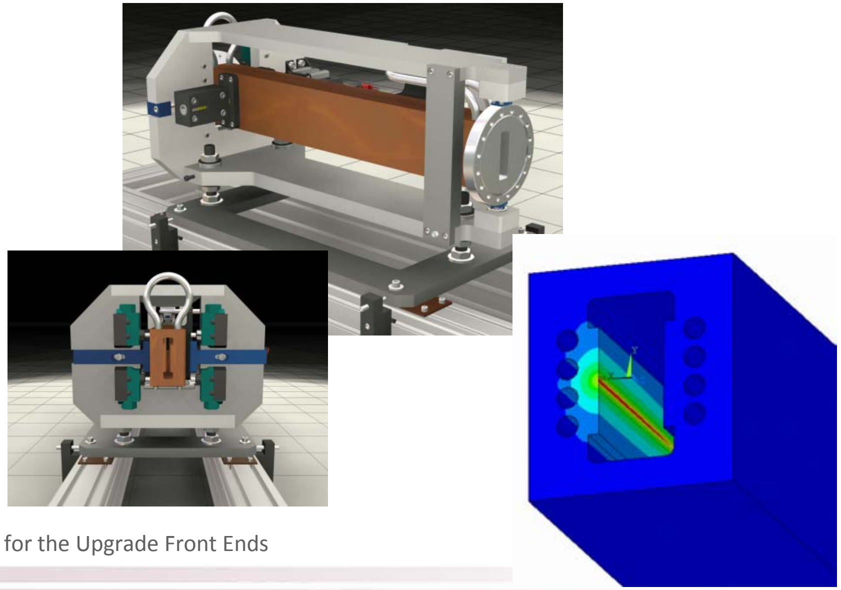
V. CU1.0 and 2.0

- Designed for 2*UA33, each 2.1 m long with 200 mA stored beam
  - Beam intercepted on horizontal surface
  - 0.9 degree incidence angle
  - 13 W/mm^2
  - Box shutter construction
- More reliable wire springs for convective heat transfer enhancement
- Used in 4 sectors
- 3 more CU Fes under construction



V. HHL

- Designed for two collinear UA33 with 180 mA stored beam
  - Beam intercepted on vertical surface
  - 1.05 degree angle of incidence
  - 33 W/mm^2
  - GlidCop plate with higher yield strength
- Used in 2 sectors (26, 30)
- 1 similar FE (IEX) under construction



APS ID Front-end power limits

	FE Vs. 1.2 Original FEs	FE Vs. 1.5 (sectors 16,22,31,320	CU FE (sectors 21, 23,24)	HHL FE (sector 26, 30)	APS-U FE
Source Parameters	One U33 at 11 mm gap at 130 mA	One U33 at 10.5 mm gap at 150 mA	Two canted 2.07 mm long U33 at 10.5 mm gap, 200 mA	Two in-line U33 at 10.5 mm gap, 180 mA	Three in-line U33 at 10.5 mm gap, 200 mA
Total Power (kW)	6.9	8.9	20	21	~ 35
Peak Power Density (kW/mrad^2)	198	245	281	590	~ 980

Limits extended by:

- Decreasing angle of incidence
- Vertical intercepting surface when possible
- Using strongest available materials for beam strike surfaces
- Careful attention to cooling

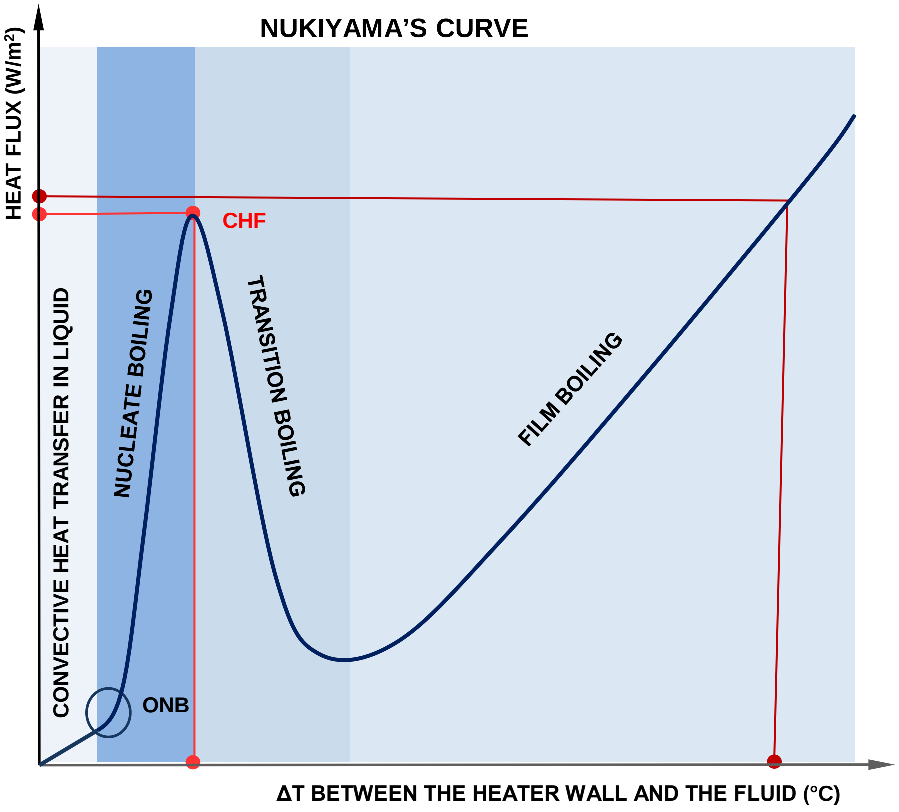
What kind of the environment do we expect after the upgrade?

- 200 mA stored beam current
- Customized Front-ends for new sources and new source configurations
- Sources must be carefully chosen to give desired tuning range and brilliance with minimal power and power density
- Choices of undulators and configurations are not fully defined at CDR. Work in progress
- Many beamlines will be able to utilize existing designs for CU and HHL FEs
- Some new sources and configurations will require Front end R&D and new Front end designs based on that R&D

Possible issues (why R&D is needed)

- Occurrence of the Subcooled Critical Heat Flux (CHF) – cooling failure
  - The APS-U ⇒ 200 mA current + long straight sections + SCU = 2 (3,4?) x current high heat loads
  - Higher heat loads mean higher heat flux heat flux from the component to the coolant
  - Occurrence of CHF is reported in similar applications (the targets of particle accelerators)
  - While we know that beam-strike surfaces can have heat fluxes greater than 25 MW/m^2, we have never investigated the magnitude of the wall-to-coolant heat flux in our components.
- Low cycle thermal fatigue - material failure
  - The stresses in HHL components exposed to the beams from 2 Undulator As with 10.5 mm gap and at 180 mA current are already very close to the yield values reported for Glidcop
  - Higher loads bring higher maximum temperatures, higher temperature gradients and, consequently, higher thermal stresses
  - Higher thermal stresses will increase the risk of fatigue failure

Subcooled CHF - - a truly complex thermo-hydraulic phenomenon



- **Definition**

CHF is a phenomenon that manifests in a **sudden and severe** drop in heat transfer efficiency.

- **Background**

It is caused by a 'blanketing' of the heat exchanger wall by vapor bubbles and its separation from the liquid core of the coolant. There are several models that try to describe the formation of vapor blankets, but no consensus has been reached.

- **Prerequisites**

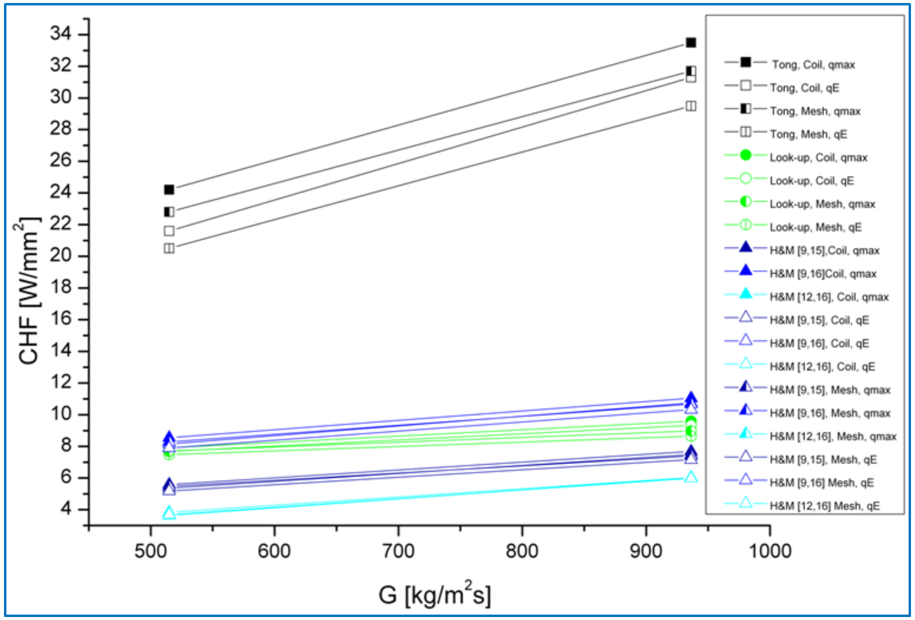
Very high wall-to-coolant heat fluxes AND wall temperatures higher than saturation temperature.

- **Consequences**

A large and instantaneous rise in the temperature of the heat exchanger wall can cause catastrophic material failure known as **burn-out**. No warning signs!

Prerequisites of CHF

- **Onset of nucleate boiling**
  - There will be no vapor film formation and thus no CHF if the heat exchanger wall temperature does not exceed, at least locally, the saturation temperature.
  - Luckily, it is relatively simple to determine if the nucleate boiling has been initiated in the system.
- **Very high wall-to-coolant heat flux values**
  - The question that the nuclear power industry has been trying to answer for more than half of a century is: how high are *the very high heat fluxes* needed for CHF to occur?
  - This enormous research effort has resulted in almost thousand related papers and more than a hundred correlations that try to predict the flux levels needed for CHF.



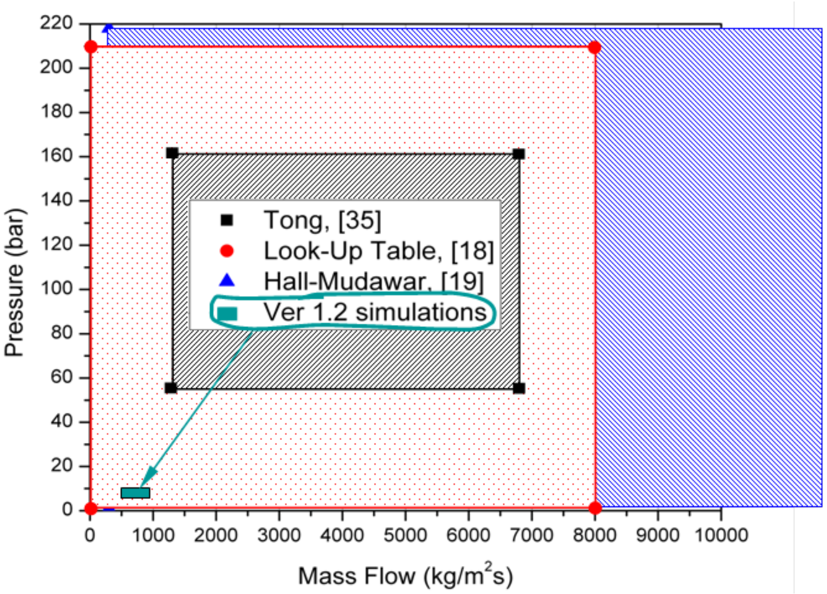
Why is understanding CHF so elusive?

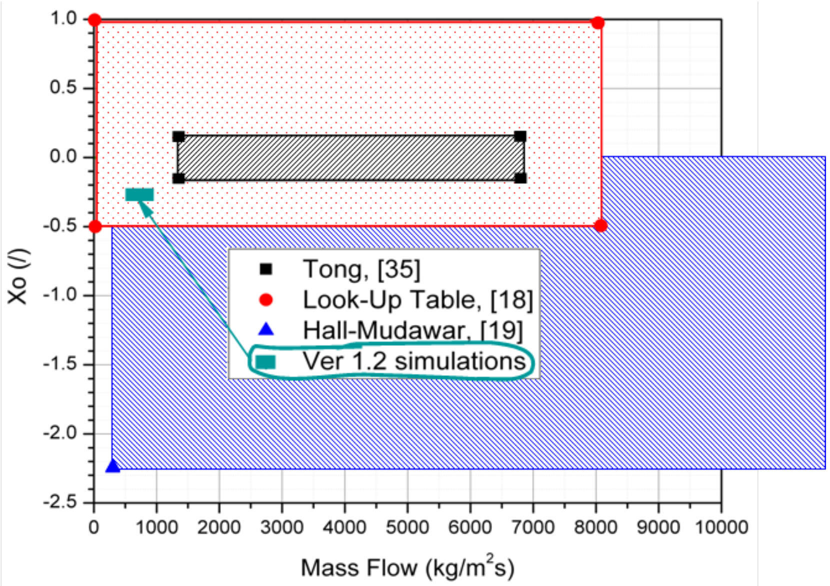
- Extensive research indicates that the CHF phenomenon is influenced by a large number of thermal and hydraulic parameters such as:
  - subcooling
  - mass velocity
  - pressure
  - geometry of cooling channels
  - flow orientation
  - spatial distribution of the heat load
  - and others…
- Large number of parameters indicates that CHF is a very complex thermo-hydraulic phenomenon. Despite tremendous effort invested, there is no generally accepted model of the subcooled departure from nucleate boiling.
- To be more precise, there are several models that are competing for the recognition as *The Model* of subcooled CHF.

The problems in predicting subcooled CHF

- There is a very large collection of experimental data that is poorly correlated
- Most of the existing experimental data and developed correlations cover the parameter ranges characteristic of the Nuclear Power Industry
- Consequently, the researchers that are investigating the occurrence of CHF in other environments often encounter a lack of appropriate correlations and a very limited number of experimental data sets suitable for comparison

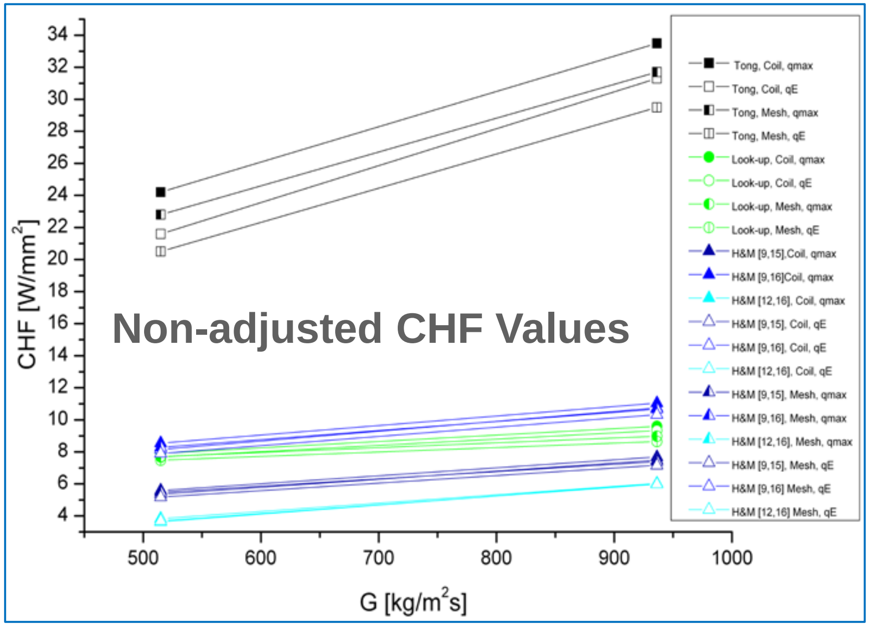
Our case





Our approach to prediction of CHF

- Predict the CHF values for channel diameter, subcooling, and mass flows similar to the ones in our components using Tong's modified correlation, Hall-Mudawar's correlations and 2006 CHF look-up table by Groeneveld et al
- Adjust the predicted CHF values to reflect particularities of our case
- Check the wall-to-coolant heat flux levels for the components that will operate in the expected APS-U conditions
- Compare computed wall-to coolant fluxes with the predicted CHF values

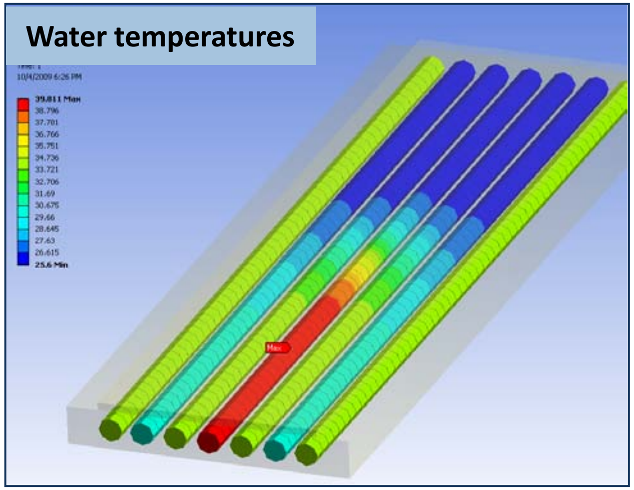


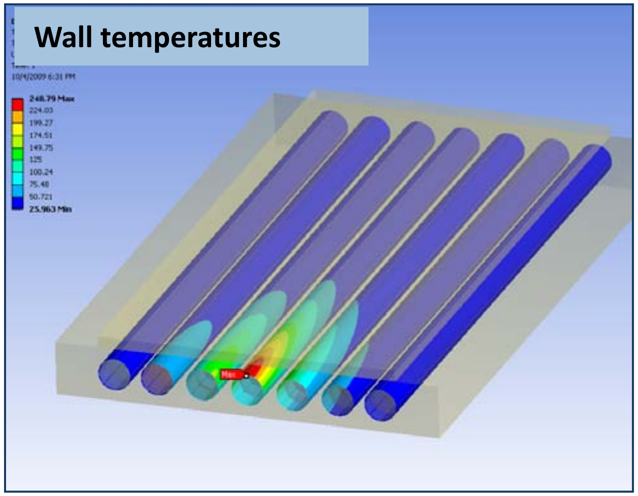
- All used correlations were developed to predict the occurrence of CHF in uniformly heated vertical tubes. Our cooling channels are nearly horizontal, non-uniformly heated and with coil inserts.
    - Correction for horizontal flow was done using Hall-Mudawar's method (2000) based on the modified Froude's number.
    - Corrections for the presence of coil inserts and for the non-uniformity of heating were based on the works of Celata et al. (1994) and Narai and Inasaka (1996)

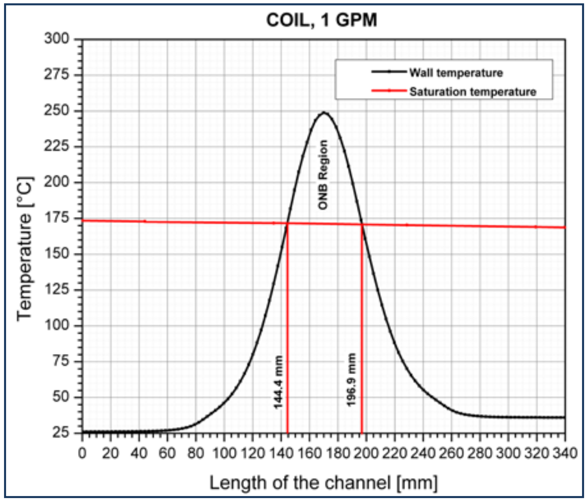
CHF correction factor

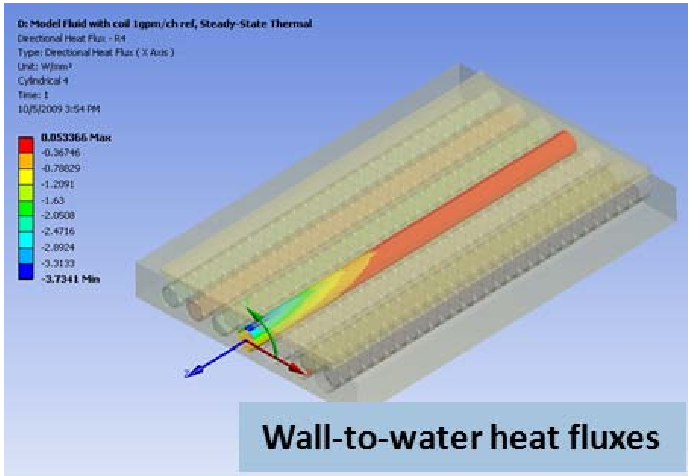
Mass Flow	K_{CHF}
515 kg/m^{2}s	0.5
940 kg/m^{2}s	0.7

FEA computations - Version 1.2 Front End


Water temperatures


Wall temperatures




D: Model Fluid with coil 1gpm/ch ref, Steady-State Thermal
Directional Heat Flux - R4
Type: Directional Heat Flux (X Axis)
Unit: W/mm²
Cylindrical 4
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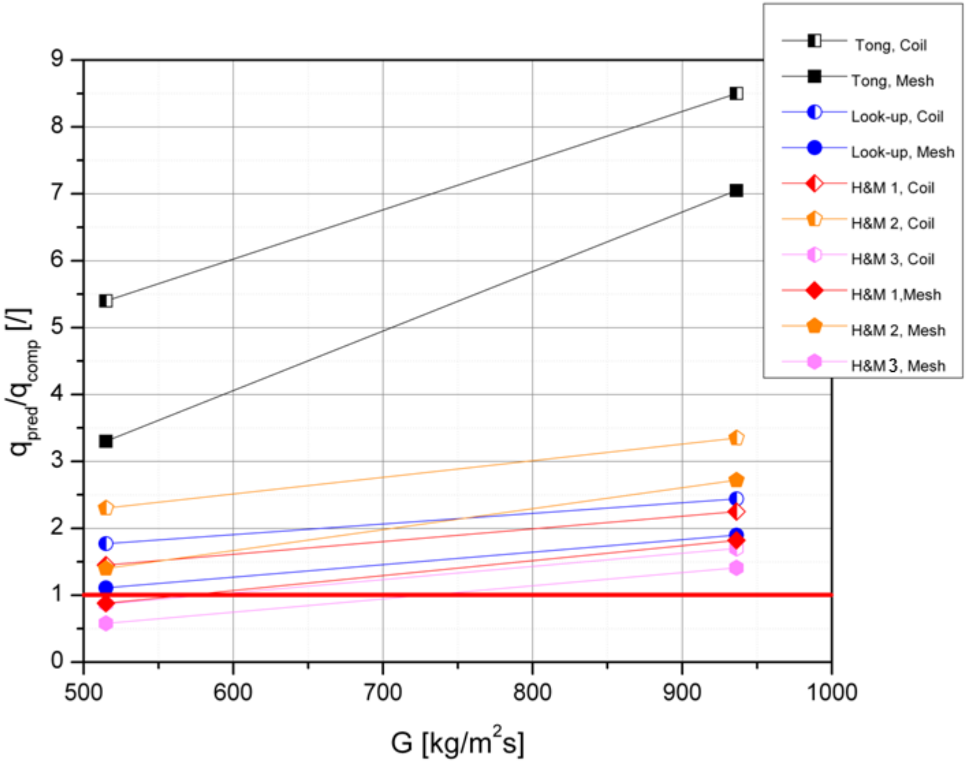
Wall-to-water heat fluxes

Calculations were made for one UA at 11 mm gap and 200mA

- ONB region is clearly present
- Wall-to-water heat fluxes are relatively high (q_{max} = 3.73x10^6 W/m^2)

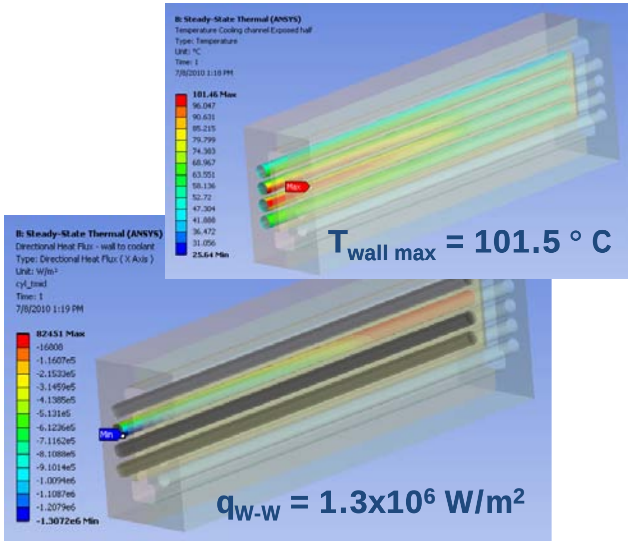
Predicted CHF Vs computed wall-to-water heat flux – Vs. 1.2



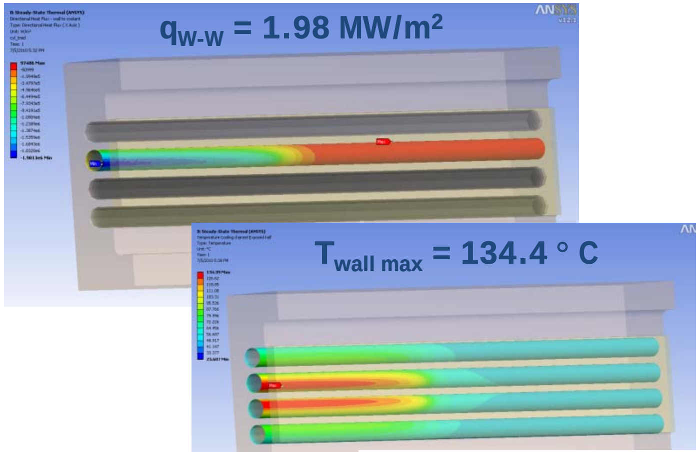
- The 'CHF Factor of Safety' for most cases is lower than 3. Only Thong's correlation consistently predicts CHF values more than three times higher than computed wall-to-water heat fluxes.
- An occurrence of CHF represents a realistic risk if the Ver. 1.2 shutters are exposed to the beam from Undulator A operating at 11 mm gap and 200 mA and the coolant flow is its allowed minimum (0.5 GPM).
- Most of the correlations predicted FoS close to or below 2 even for nominal coolant flow (1 GPM).
- Two recommendations for APS-U are:
  - to increase the minimum coolant flow to 1 GPM,
  - to replace all Ver. 1.2 Front End components

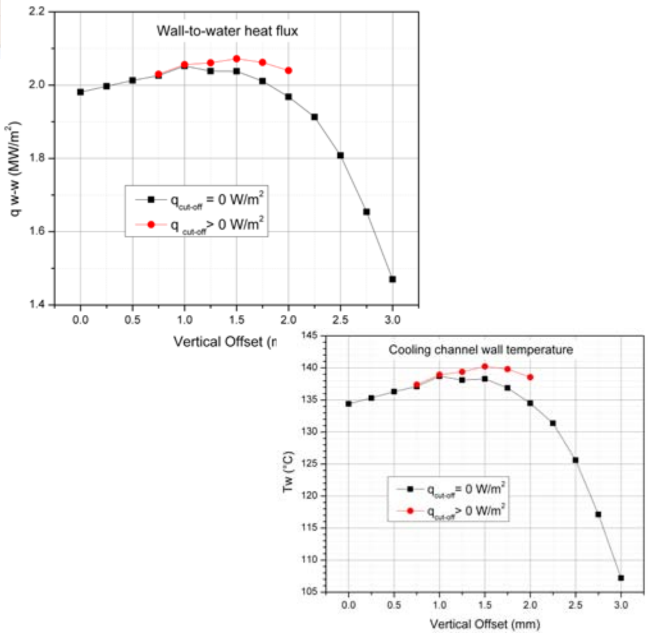
FEA Computations – HHL Front end

2 UNDULATOR As, 10.5 mm gap, 200 mA



3 UNDULATOR As, 10.5 mm gap, 200 mA





- CHF occurrence does not represent an operational risk for the HHL shutters exposed to the beams generated by dual inline undulators
- Wall-to-water heat fluxes and cooling wall temperatures in HHL shutters exposed to the beams generated by three inline undulators remain bellow critical values, with maximum computed wall-to-water heat fluxes reaching 60% of the minimal predicted CHF values
- Vertical missteering can increase both wall-to water heat fluxes and cooling channel wall temperatures but not significantly
- Additional source configurations should be analyzed

And now something completely different…

Low-cycle thermal fatigue

- Well(Long?) known engineering problem
  - Thermal cycling results in accumulated strain which eventually leads to the development of cracks at strained surfaces
  - ‘Low-cycle’ implies that at least a part of structure is plastically deformed and that number of cycles that leads to failure remains bellow 100 000
- Cracks may lead to vacuum failure, cooling failure, or topography changes that result in increased thermal load and subsequent failure
- Research performed at APS and at SPring-8 suggests possibility that thermal loads could be increased to as much as 50 W/mm^2 (1.8 X HHL loads) without causing uncontrolled and catastrophic material failure

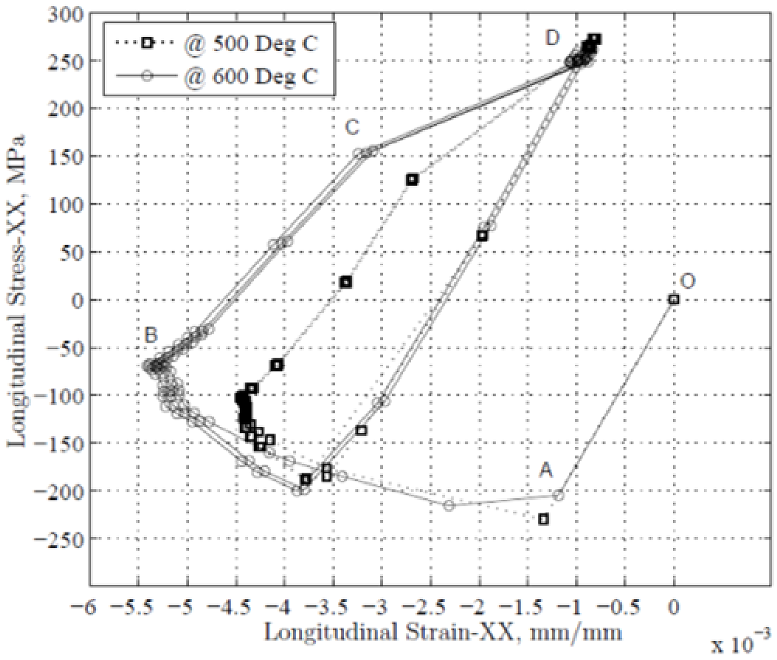


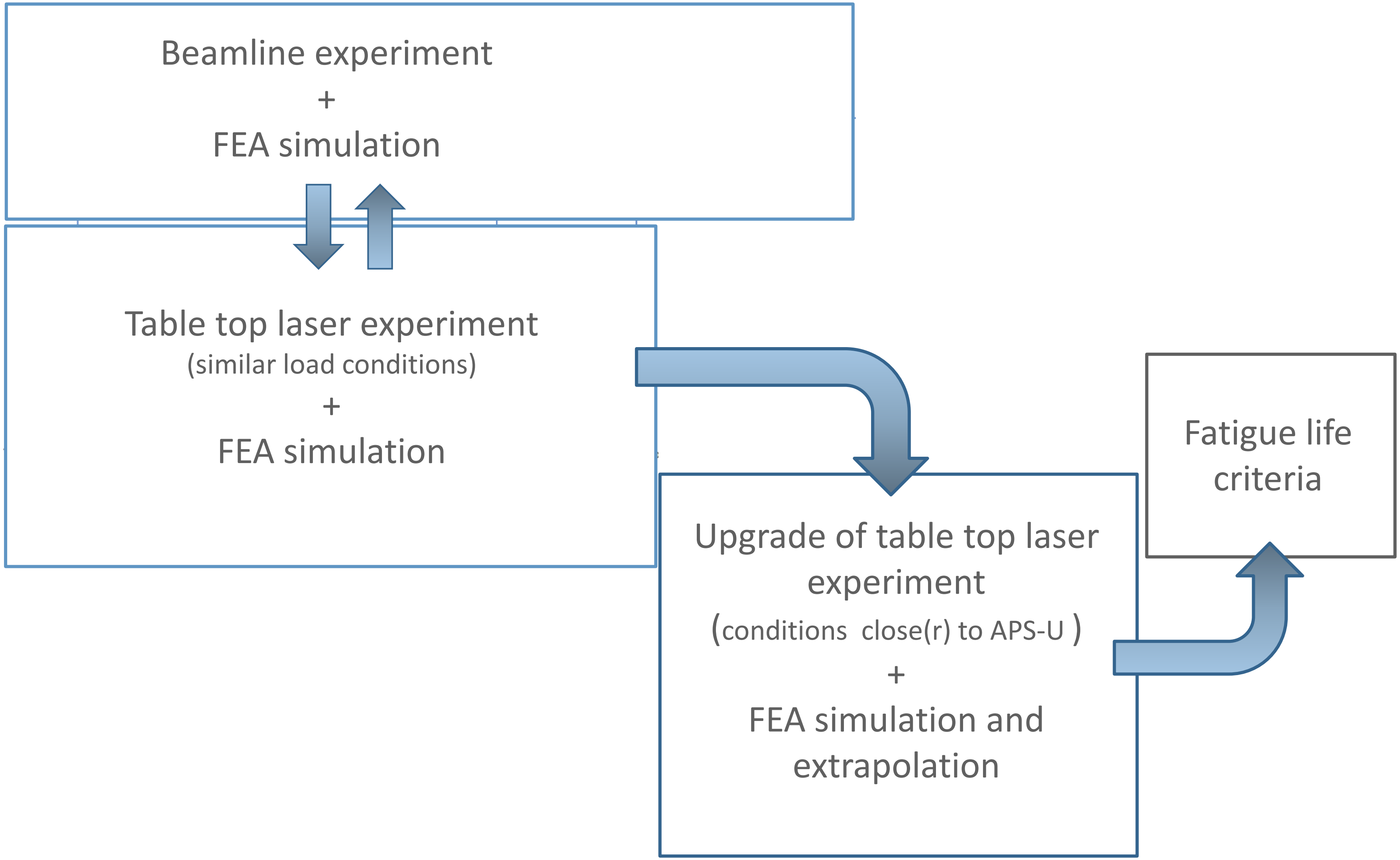
Figure 4.14. Hysteresis plot-stress-xx vs strain-xx at the center of the beam footprint for a peak temperature of 600° C and 500 ° C

V. Ravindranath, S. Sharma, et al. (2006). Thermal Fatigue Life Prediction of Glidcop® Al-15. MEDSI 2006, Himeji, Japan.

Low-cycle thermal fatigue as we know it

- **Research done so far**
  - Study at ESRF in collaboration with APS - 2005
  - Study at APS, Phase I – 2005-2006
  - Study at APS, Phase II – 2006-2007
  - Study at SPring-8 – 2006-2008
  - Preliminary computations indicate that certain source configurations planned for APS-U will cause plastic deformation and , thus, thermal fatigue induced material damage
- **Conclusions reached**
  - Very difficult to draw a clear conclusion from the studies
  - The APS approach developed by V. Ravindranath attempted to establish the thermal fatigue life predictions in terms of only peak surface temperature
  - Thermal fatigue life is directly related to thermal strain conditions and thermal strain conditions have to be included in establishing thermal fatigue life predictions
  - The SPring-8 study is more comprehensive and correctly relates the thermal fatigue life to both the temperature and thermal strain
  - The SPring-8 test approach with only few hundred thermal cycles to failure is questionable
  - We will most likely have to live with the Front end components exposed to the thermal fatigue damage and will have to develop design criteria that will guarantee safe operation (similar to the aviation industry)
  - Adequate experimental research with several thousand cycles to failure is needed to relate the thermal fatigue life to temperature and thermal strain

New fatigue life experiment - initial plan



Beamline experiment
+
FEA simulation

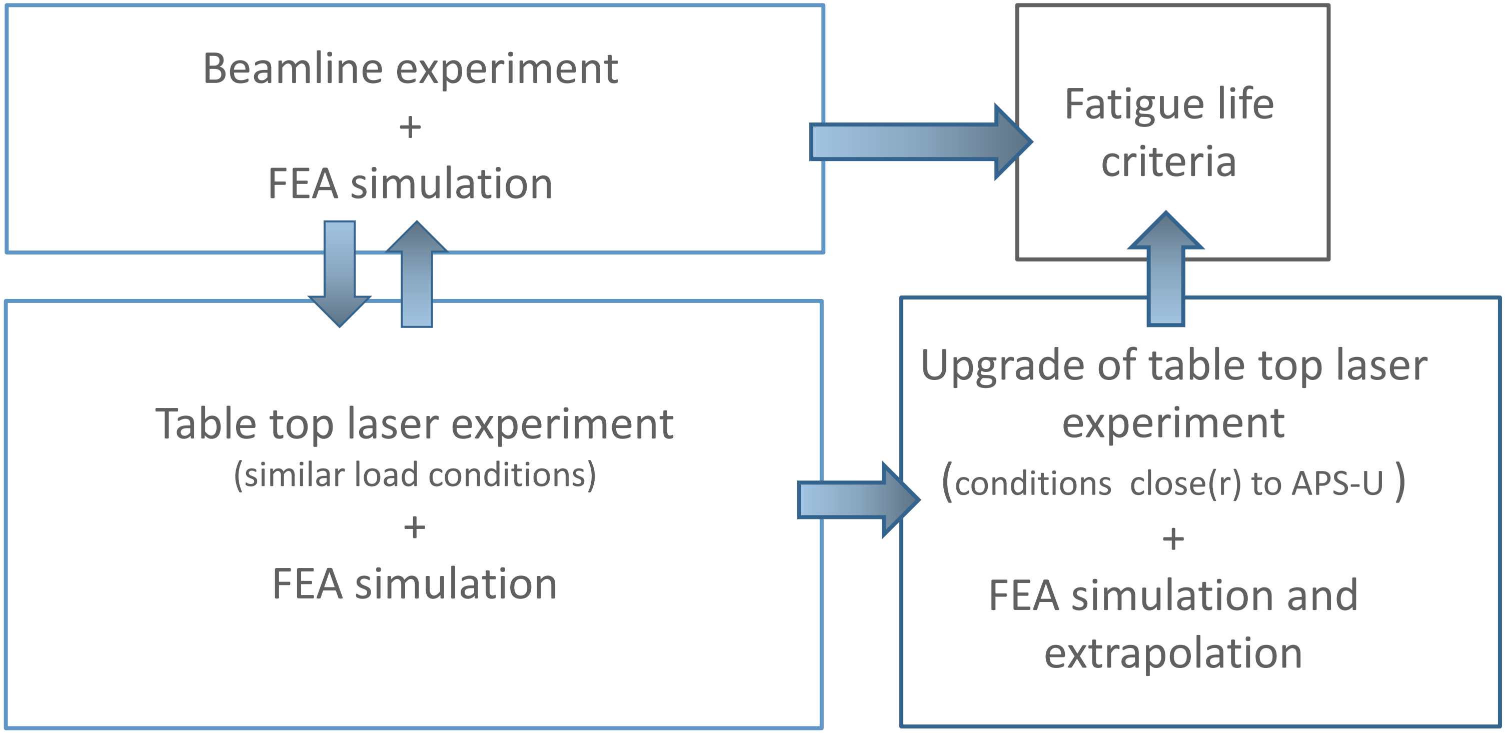
Table top laser experiment
(similar load conditions)
+
FEA simulation

Upgrade of table top laser experiment
(conditions close(r) to APS-U)
+
FEA simulation and extrapolation

Fatigue life criteria

New fatigue life experiment – as of now

- **After several discussions of our initial plan with the management of we were able to:**
  - Better focus our goals
  - Significantly reduce the cost of the experiment



Beamline experiment
+
FEA simulation

Fatigue life criteria

Table top laser experiment
(similar load conditions)
+
FEA simulation

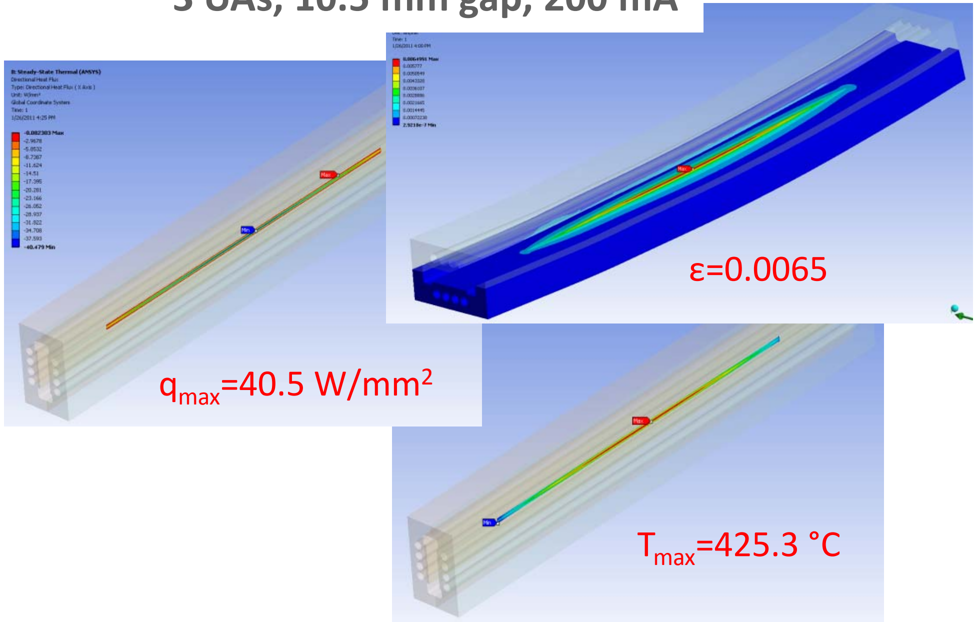
Upgrade of table top laser experiment
(conditions close(r) to APS-U)
+
FEA simulation and extrapolation

- However, we still work on the plan and hope that we will come up with a truly optimized experimental plan

Beamline Vs table top approach

- Beamline experiment
  - Provides ‘real life’ source and realistic interaction of the x-ray beam and the intercepting surface
  - Cost is reasonable
  - Experimental procedure is known
  - Fails to provide ‘right’ combination of the intercepting surface temperature and developed thermal strains:
    - EITHER surface can be strained to the expected level but the temperatures will be higher
    - OR surface can be at the expected level but the strain will not reach expected level
    - Properties of Glidcop are temperature dependant and it is to be expected that fatigue life will be too

3 UAs, 10.5 mm gap, 200 mA

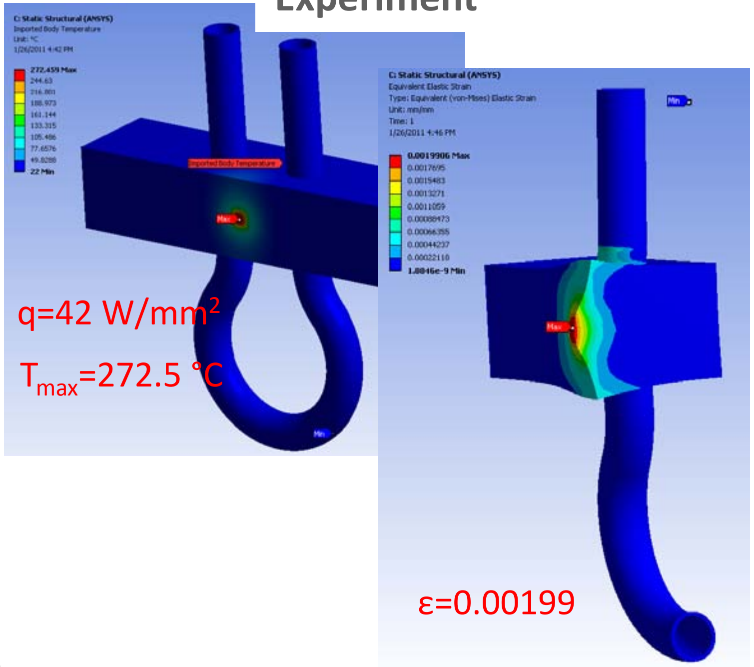


ε=0.0065

q_{max}=40.5 W/mm^2

T_{max}=425.3 °C

Experiment



q=42 W/mm^2

T_{max}=272.5 °C

ε=0.00199

Beamline VS table top approach - continued

- Table top experiment
  - Provides surrogate source resulting in interaction of the optical beam and the intercepting surface
    - Optical laser beam does not interact with the intercepting surface in the same way as X-ray beam does

      (optical beam does not penetrate intercepting surface, no Compton scattering, no Bragg diffraction)
    - Efficiency of energy coupling could be an issue (high reflectivity of copper surfaces)
  - Cost is high
  - Experimental procedure has to be developed
  - Can provide combination of the intercepting surface temperature and developed thermal strains that is much closer (or even similar) to ones expected after APS-U
    - Beam does not have to have normal incidence (flexibility of beam footprint geometry)
    - Thermal load levels can be precisely engineered by choosing multiple lasers
    - Geometry of the beam footprint can be additionally manipulated by focusing optics
  - No ‘available beam time’ limitation
  - Table top experiments can be performed in phases and independent of the beamline experiments

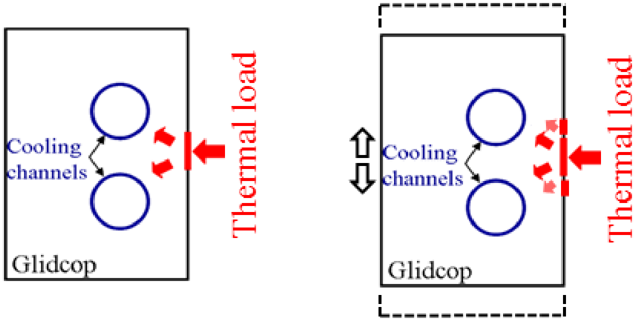
(First) Beamline and (then) table top experiments?

- **LDRD proposal covering beamline experiment submitted**
  - Based on the existing equipment and previous effort at APS
  - Several improvements introduced
    - Investigation of the effect of the surface quality on fatigue life added
    - Each experimental sample will have two sides sequentially exposed to the beam thus doubling the amount of data per sample
    - Referent (initial) sample surface condition is recorded
    - FEA simulations will be used to relate fatigue life to both temperature and strain
    - Sample design modified to lower production costs
    - An attempt to optimize heating-cooling cycle length is under way
  - Activities are in progress
    - First two sets of experimental samples are made
    - One set is in the finishing phase of metallurgical testing
    - All the equipment is collected and ready for assembly and testing
    - Preparation of review documentation is in its finishing phase
    - We expect to start the experiment in the second half of February
- **We are preparing a provisional test set-up for Laser table top experiment**
  - A vendor promised to lend us one laser unit for at least 30 days and at no cost
  - We are altering one existing experimental vacuum chamber for the purpose of the provisional test
    - We will address the issues related to the use of laser beam as the heat load source
- **We continue to investigate alternative heat sources for the table top experiment**

New designs for APS-U

Possible avenues for improvement

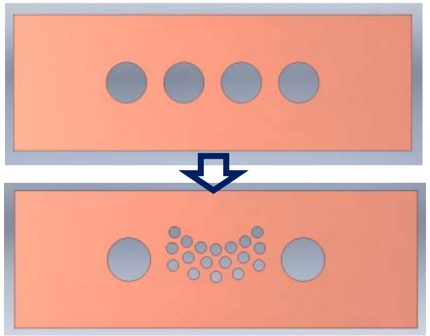
- Designs optimized for in-situ inspection
  - Existing methodology
  - Non-destructive early warning technology now available
  - Relatively moderate production cost increase
  - Time consuming interventions required
  - Extensive mechanical redesign
  - Limited reliability – human factor involved
  - Limited reliability – lack of accurate criteria
  - Fast failure mechanisms (CHF) must be prevented
- Raster Cooling
  - Existing technology
  - Relatively moderate production cost increase
  - Moving mechanism involved
    - Expected higher failure ratio
  - Complex optimization needed for noticeable increase in heat transfer efficiency

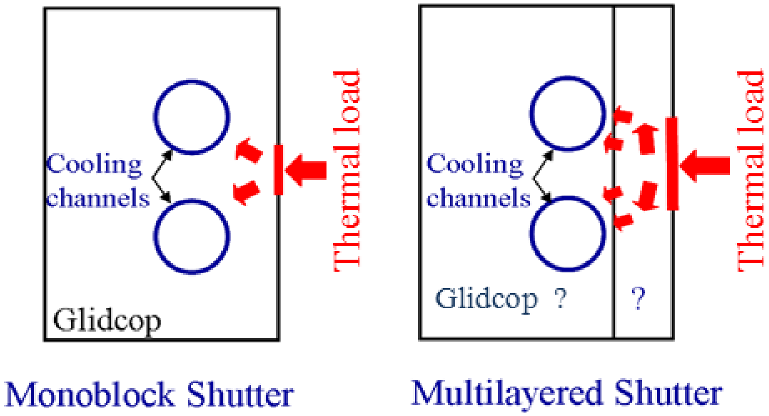


New designs for APS-U

Possible avenues for improvement

- **'Micro' channels**
  - Existing technology
  - Moderate production cost increase
  - Hydraulic side effects
  - Complex optimization needed for noticeable increase in heat transfer efficiency
  - Expected higher failure ratio
- **Thermal spreaders**
  - Beryllium
    - Existing technology
    - Moderate improvement in heat transfer
    - Production cost increase
    - Safety issues
  - Pyrolytic graphite or diamond
    - Considerable improvement in heat transfer
    - Semi-existing technology
    - Semi-existing technology (good thermal and mechanical bond hard to achieve)
    - High to very high production costs





New designs for APS-U

Possible avenues for improvement

- **Phase change cooling (deliberately induced boiling)**
  - Existing technology
  - Very large increase in heat transfer
  - Highly increased CHF risk
    - Extensive related R&D required
  - Possible high cost due to the pressure issues
  - Vibrations
- **Material improvement techniques (pre-stressing)**
  - Existing technologies (various peening technologies)
  - Engineered improvement in material properties
  - Possible incompatibility with other production techniques
    - Possible extensive redesign to resolve incompatibilities
- **New materials**
  - Properties engineered to better meet our harsh requirements
  - Yet to be discovered

Summary

- Existing CU and HHL Front-end designs can meet the requirements for many of the APS Upgrade beamline front-ends
- A number of new front-end configurations are needed for APS Upgrade beamlines
- Currently, APS design rules limit the sources that can be used
- Reliability testing and analysis may allow the thermal load limits to be increased moderately
- New design philosophy will be needed for very high heat load sources
- R&D needed for formulating new Front end design criteria is under way
- R&D will require continuing effort and at least some level of funding