A Discussion on Utilization of Heat Pipe and Vapor Chamber Technology as a Primary Device for Heat Extraction from Photon Absorber

Kamlesh J. Suthar, Alexander Lurie, & Patric Den Hartog

Advanced Photon Source

Engineering Support Division

Argonne National Laboratory, USA

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MECHANICAL ENGINEERING DESIGN OF SYNCHROTRON RADIATION EQUIPMENT AND INSTRUMENTATION

BARCELONA

Outline

- Problem Description
- Result of Water Cooled Design
- Heat Pipe
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  - Theoretical Limitations of Heat Transport
- FEA
  - Recommended methods
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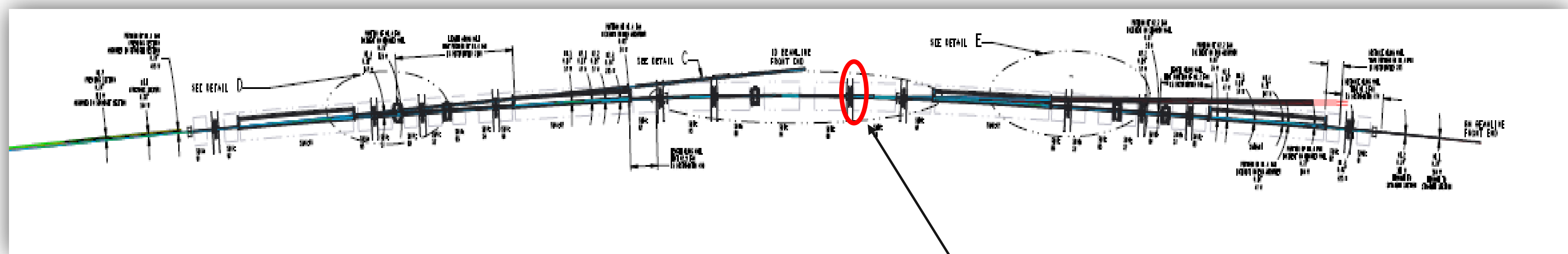
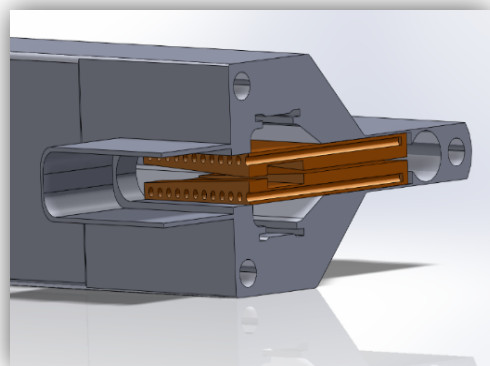
- FEA (cont.)
  - 3 Layers & Rule of Thumb Conductivity
  - Small Temperature Drop
  - FEA Results
- Alternatives
- Conclusions

Problem Description

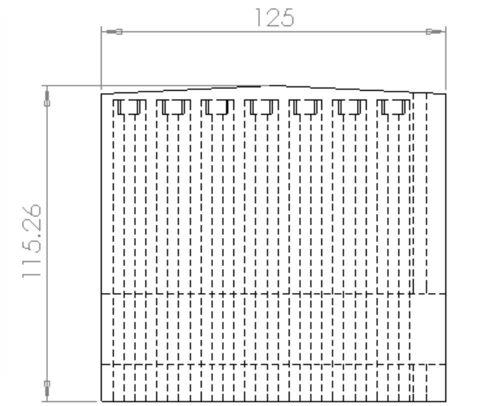


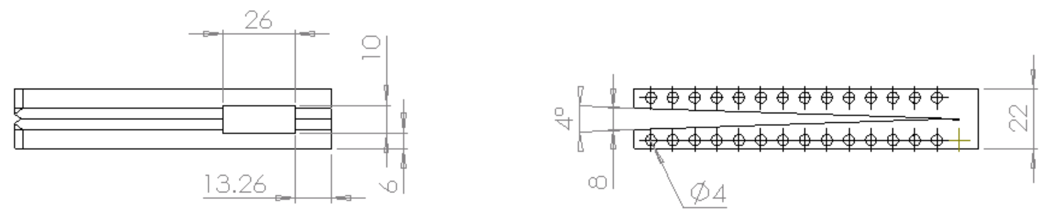
FEA Thermal Steady State Analysis [1]

- Current Design of B:CA1
  - 2.9KW
  - Limited space
- Problems
  - Max. Temperature
  - Temperature Gradient and Thermal Stresses



B:CA1 Absorber in Assembly [1]

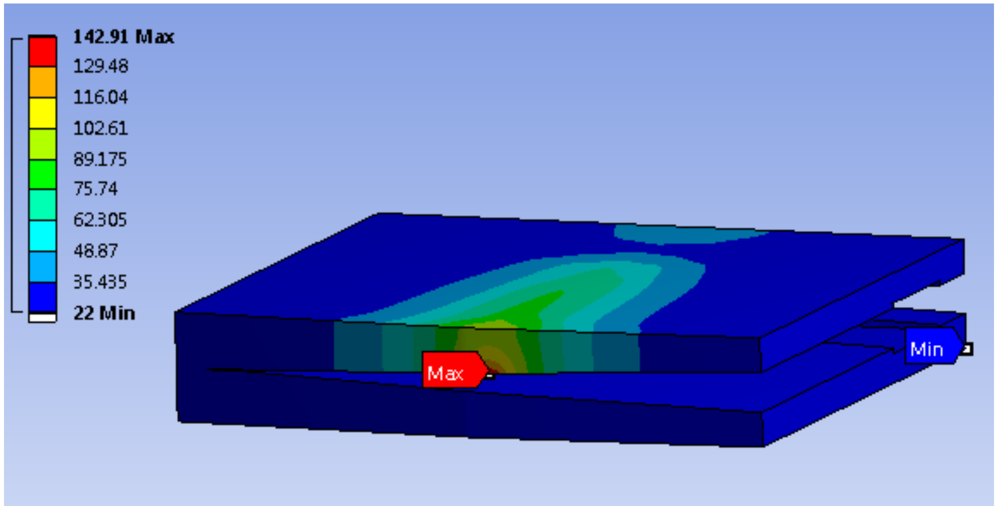




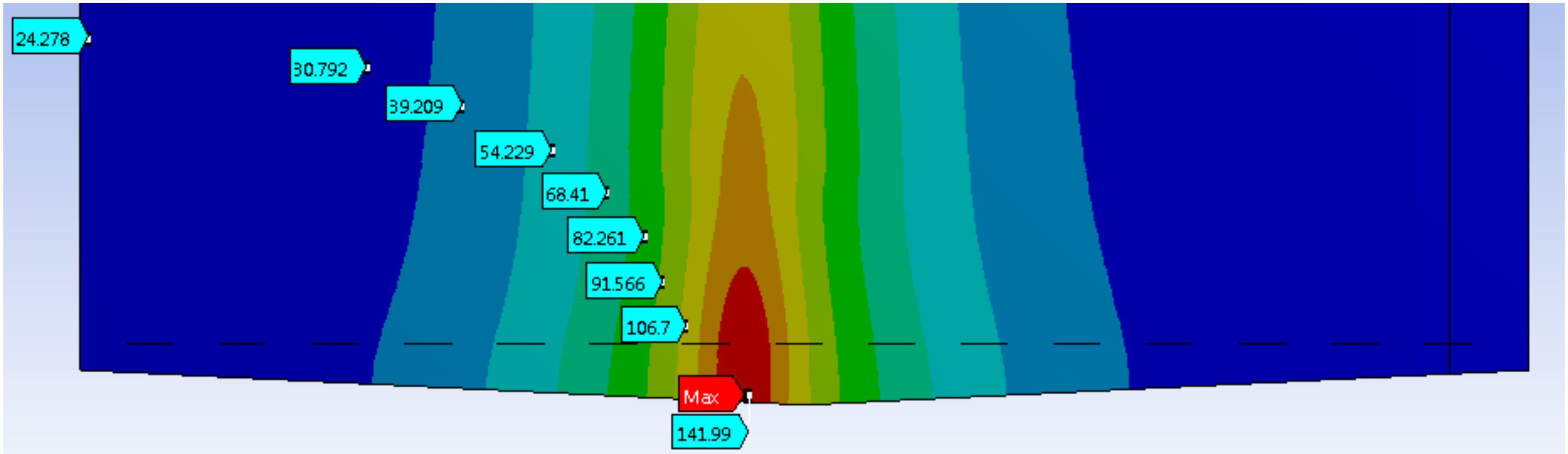
B:CA1 Drawing [1]

FEA Result of Baseline Design

- Thermal Analysis of B:CA1
  - Worst Case Scenario
  - Risk Imposing Thermal Gradient
  - High Maximum Temperature



Water Cooled Thermal Steady State FEA



The Heat pipe

What is the Heat pipe?

- Heat pipe
- Image from Vendor

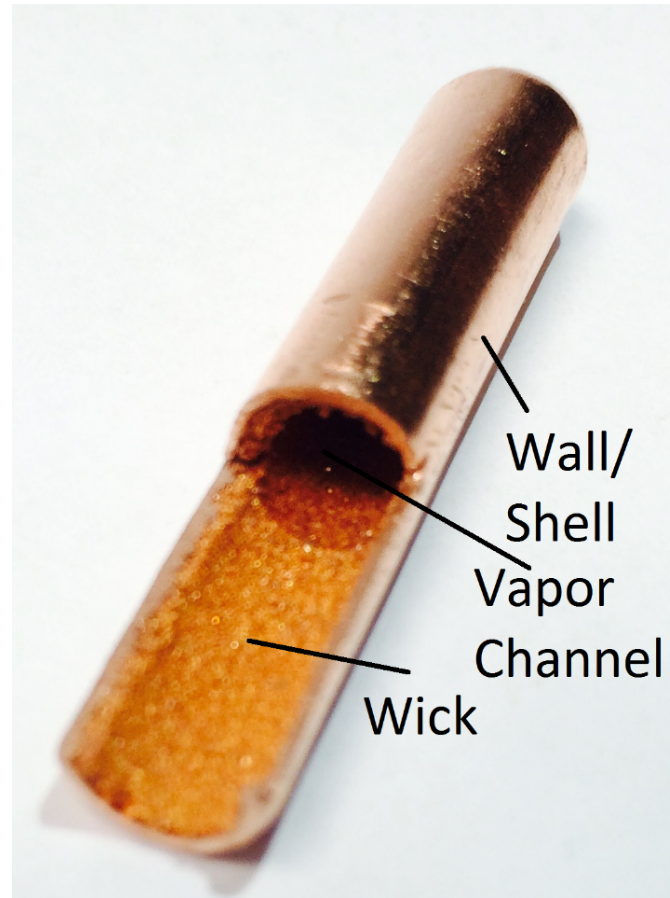
Ref: http://www.thermoguide.co.il/Heat_pipes.html

Heat Pipe Background

- Flow within the heat pipe
- Figure from Vendor

Heat Pipe Flow Diagram[2]

- Two Phase Heat Transport Device
  - Phase Change Phenomenon w/ Anti-Parallel Flow
  - Large Variety of Wick Types
  - Flexible Geometry
  - Low Vibration Expectations
  - ***Equivalent*** Thermal Conductivity that is 10 to 1000 times higher than metal in same shape



Copper-Water Sintered Powder Heat Pipe (Cut Open)

hc = 5000 - 200,000 $W/m^2/K$

k = 2000 - 100,000 W/m/K

Advantage and Limitations

Typical Characteristics of heat pipes

Advantages:

- Very high effective thermal conductivity **(~100 kW/m/K)** compared to Cu **(0.4kW/m/K)**
- **Vibration free** operation can be possible
- Can transport heat to a **large distance**
- They offer the possibility of **more compact design** and efficient means to remove heat
- Long Operating **Life** (**20+ years**) without any maintenance.
- Final heat removal can be done via conduction, or radiation heat transfer

Heat pipe limits-operating envelope

- Transport Limitations
  - Viscous/ vapor pressure
  - Sonic
  - Entrainment
  - Boiling
  - Capillary Pressure

- Heat pipe limits–operating envelope
- Figure from Vendor

Reference: http://www.thermopedia.com/content/835/

Example Heat Pipe Limitation Graph from Industry Vender [3]

Vapor Pressure or Viscous Limit

- Usually occurs at start-up
- The minimum pressure at the condenser end of the pipe can be very small due to cold or hot start up and difference in temperature.
- The **vapor pressure drop between the extreme** end of the evaporator and the extreme end of the condenser, represents a restriction in operation.

Sonic Limit

- At a temperature above the vapor pressure limit in the heat pipe, the **vapor** velocity can be comparable with **sonic velocity**
- At this point, the **vapor flow** with in the heat pipe **becomes "choked".**
- To avoid choked flow conditions (i.e., sonic limit) is to work below this limit of the maximum rate of heat transfer.

Reference: http://www.thermopedia.com/content/835/

Entrainment Limit

- The **vapor velocity increases** with temperature and may produce very high **shear force** on the returning liquid flow from the condenser to the evaporator, which cause entrainment of the liquid towards evaporator by the flow of vapor.
- The restraining force on **liquid** counter by **surface tension, that** is a major parameter in determining the entrainment limit. Entrainment will cause a starvation of fluid. Restriction of fluid flow from the condenser and eventual "*dry out*" condition at the evaporator.

Reference: http://www.thermopedia.com/content/835/

Circulation Limit

- The **driving pressure** for liquid circulation within the heat pipe is given by the capillary force established within the wick structure, given by following equation.

$$\Delta p_{\sigma} \geq \Delta p_1 + \Delta P_v + p_1 g l \cos\phi$$

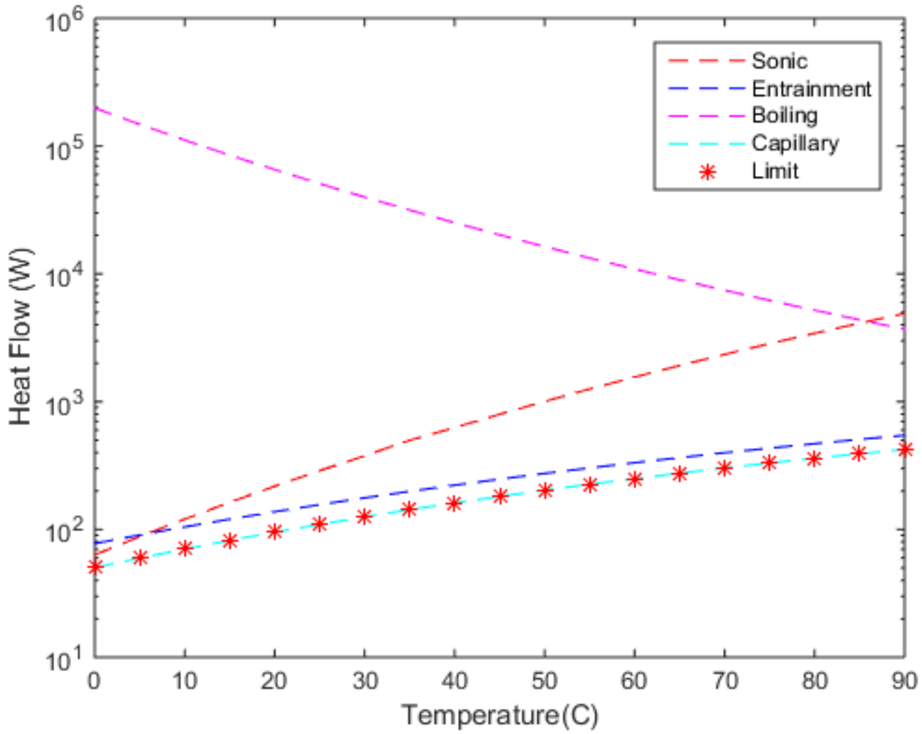
where Δpl is the frictional pressure drop in liquid and Δpv is the factional pressure drop in the vapor.

Boiling Limit

- Excessive heat input can create this condition. The **temperature drop** across the wick structure in the evaporator region **increases** with increase in incoming heat flux.
- A point is reached when temperature difference exceeds the degree of superheat that can not sustain in relation to nucleate boiling conditions. This condition of the **onset of Boiling** within the wick structure can **interferes with liquid circulation**. This can lead to the "*dry out*" condition, while in the case of constant heat flux, this can cause "**Burn Out**" of the evaporator containment.

Theoretical limits of Heat Pipe

Heat Transfer Limitations on Feasible Heat Pipe Design



Heat Pipe Limitation Plot

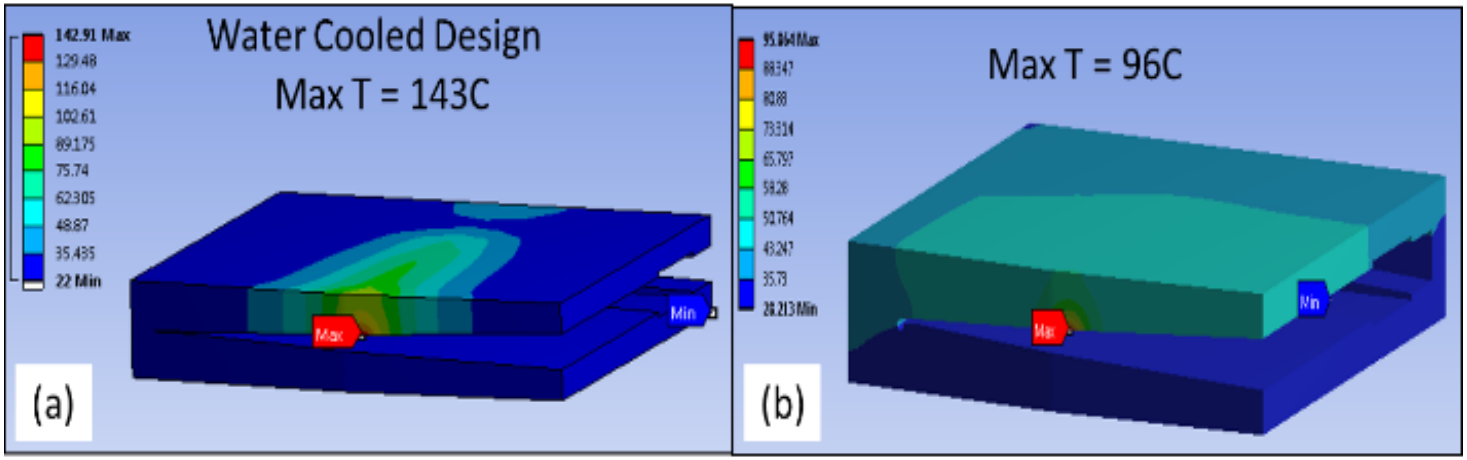
- MATLAB
  - 1000+ lines w/ GUI
  - Outputs
    - Limitations Plot
    - Figure of Merit Plot
    - Maximum Heat Transport
    - Thermal Resistance
    - *Equivalent* Thermal Conductivity
    - Other characteristic values
  - Optimization on Design Parameters

Finite Element Analysis

FEA cases

1. Pipe is modelled as a **hyper conductive rod** by equivalent thermal conductivity
2. **Multiple layers** of the heat pipe are modelled
3. Variations on the **hyper-conductive rod and multiple layer** model simulations are performed which treat temperature as a constant 2-5℃ difference and alter the conductivities to achieve this.
4. Treat the **heat pipe's temperature difference** as a few degrees constant. Set the contact thermal conductance to change the thermal conductivity of the heat pipe to achieve desired temperature change.

FEA Comparison



- Generally, it was found that, regardless of the method used, a **heat pipe reduces the temperature** gradient on the absorber surface
- The **worst-cases scenarios** showed only a marginal improvement
- while others indicated a **larger benefit is achievable**, but all cases suggested that the heat pipe is a reasonable option in this application.

FEA Results

- **Maximum Temperature often lower**, but when higher it still is within a reasonable range and only in the overestimate methods

- **Temperature gradient** improved even in worst of models

Is it reliable?

RELIABILITY ISSUES

Start-up Conditions

- During start up the **temperature gradient** may vary considerably.
- Conditions such as – **non uniform distributions** of the fluid, which lack condensable gases resulting in a **sudden drop off in temperature**.
- **Failure is a legitimate concern** under such conditions.

Structural Stability

- It is important to note that heat pipes may be required to **withstand vibrations, shock, and severe temperatures**.

- Copper and GlidCop™, may be used to construct a heat pipe with very thin walls owing to the strengths of those materials.

Reliability Issues continued....

- Possibilities include: **capillary pumping failure, boiling, dry-out from a frozen fluids restricting the self-replenishing nature, and entrainment of the liquid flow**.
- In addition, **low thermal resistance at the condenser** can overwhelm the system and enhance the probability that such failures will occur.
- There are **ways to avoid some of these failure modes**, for example utilizing an entrainment limit which exceeds sonic limit.
- However, solutions to such problems, and the degree to which they may be avoided are strongly dependent on the **specific application.**

Manufacturing Concerns

- The development of a **shell**, the insertion of a **wick**, and filling the pipe with fluid as it is sealed off at one of the ends.
- Afterwards, some **experimentation** is need on any given heat pipe to **ensure it performs as intended**.
- At the same time, to achieve the design needed, **the evaporative section needs to be built into the absorber** itself for all the heat pipes.

- The precise of manufacturing methods can also generate **heat pipe with different pressure** in each product and it does offer **concerns that arise from manufacturing process.**

Contact Variance

- Another major concern is the thermal interaction between the heat pipe and the absorber.

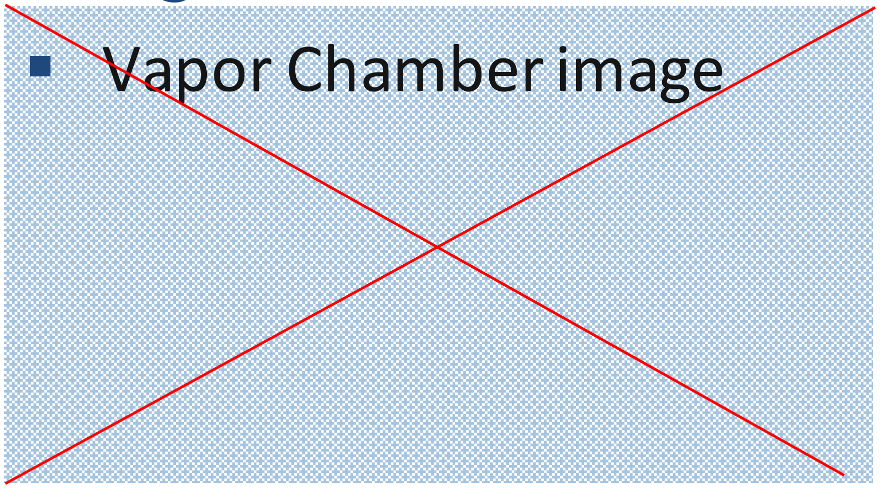
Material Compatibility for Operation

- Some fluid and solid combinations will result in chemical reactions that develop gas pockets which hamper or cease operation of the heat pipe.
- Water is known to be generally compatible with copper however compatibility between water and GlidCop™- another common absorber material, is less established.
- The Acetone or some refrigerants would be some potential alternatives by being compatible with both.
- However, these would offer notable downgrades in performance capabilities.

Solution?

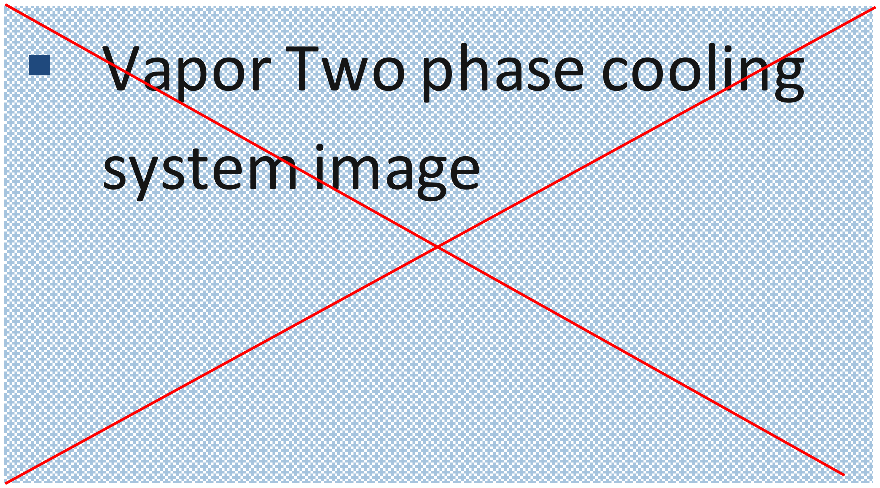
Other Two-Phase Heat Exchanger Solutions

- Flat Heat Pipe ("Vapor Chamber")
  - Geometric Challenge
  - Spreads Effectively



Vapor Chamber [5]

- Pumped Two Phase Cooling
  - Typically Isothermal
  - High Heat Flux Capacity
  - Requires Lower Flowrate



Pumped Two Phase Cooling Diagram [6]

Conclusion

- **Heat pipes offer an attractive solution** for efficient and compact transport of heat in photon absorber applications.
- **Simulations** show that heat pipes offer **tangible improvements** over conventional water cooling.
- However, a number of **potential limitations** should be weighed against the performance improvements.
- These include potentially more complex and **costly fabrication**, **limited operational predictability**, and **reliability**.
- **Continued investigation is warranted**, particularly as the requirements for next generation accelerators continue to become more challenging.

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Questions?

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