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Transient heat transfer to He II due to a sudden loss of insulating vacuum*

Ernesto Bosque & Steven Van Sciver

National High Magnetic Field Laboratory

Mechanical Engineering Department

Florida State University

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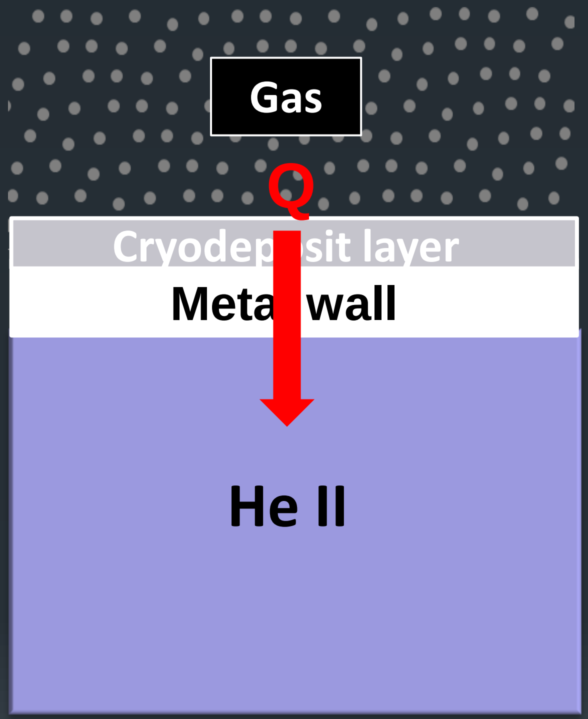
Motivation

- Sudden loss of vacuum in cryogenic systems
  - Condensation of gas generates heat fluxes to He II
  - Gas in vacuum space provides thermal link between cryogen and ambient environments
- As of yet, there is still only sparse empirical data concerning the fundamental cryodeposition process
- Experiments performed here provide both qualitative and quantitative observations of general cryodeposition behavior and heat fluxes specific to He II-cooled systems

  Qualitative –
  - Mass transport is observed to be governed by heat transport processes

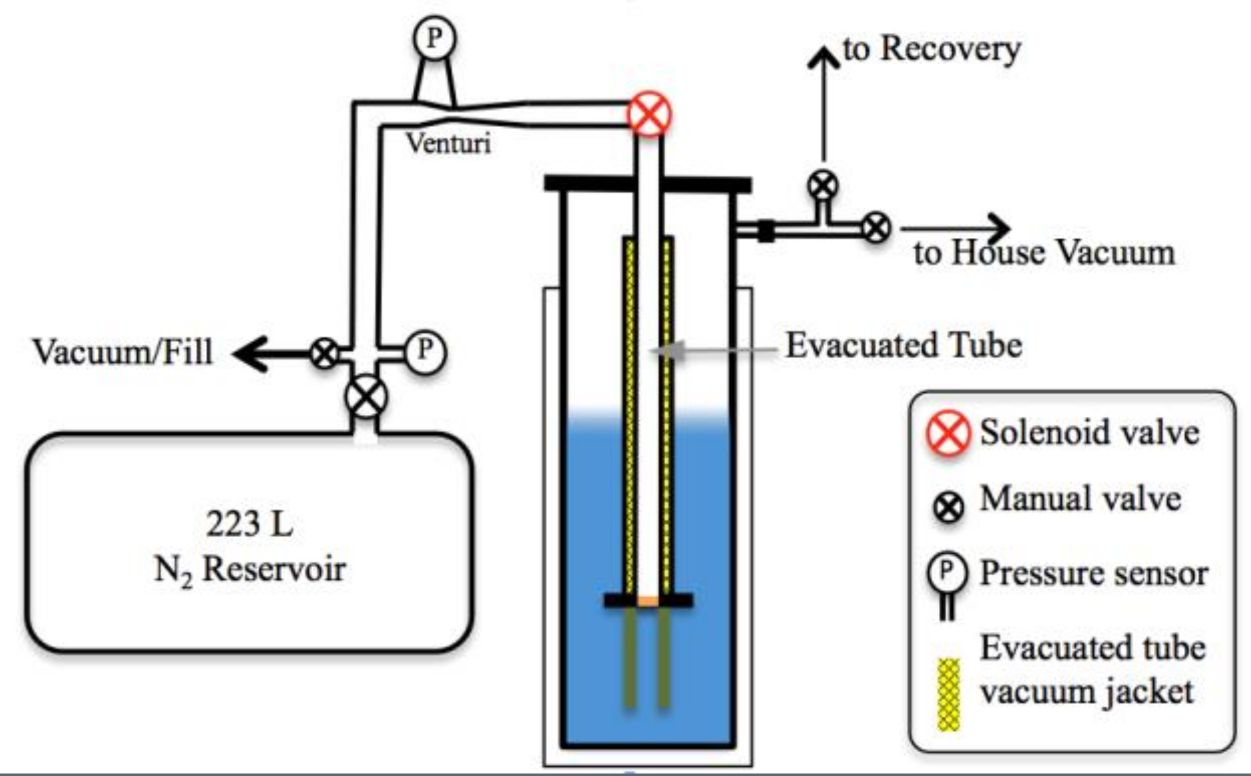
  Quantitative –
  - Coupled heat transport mechanisms limited by the thermal diffusion through thickening cryodeposited substrate



Experimental Design

Experiment built to simulate a real world vacuum failure

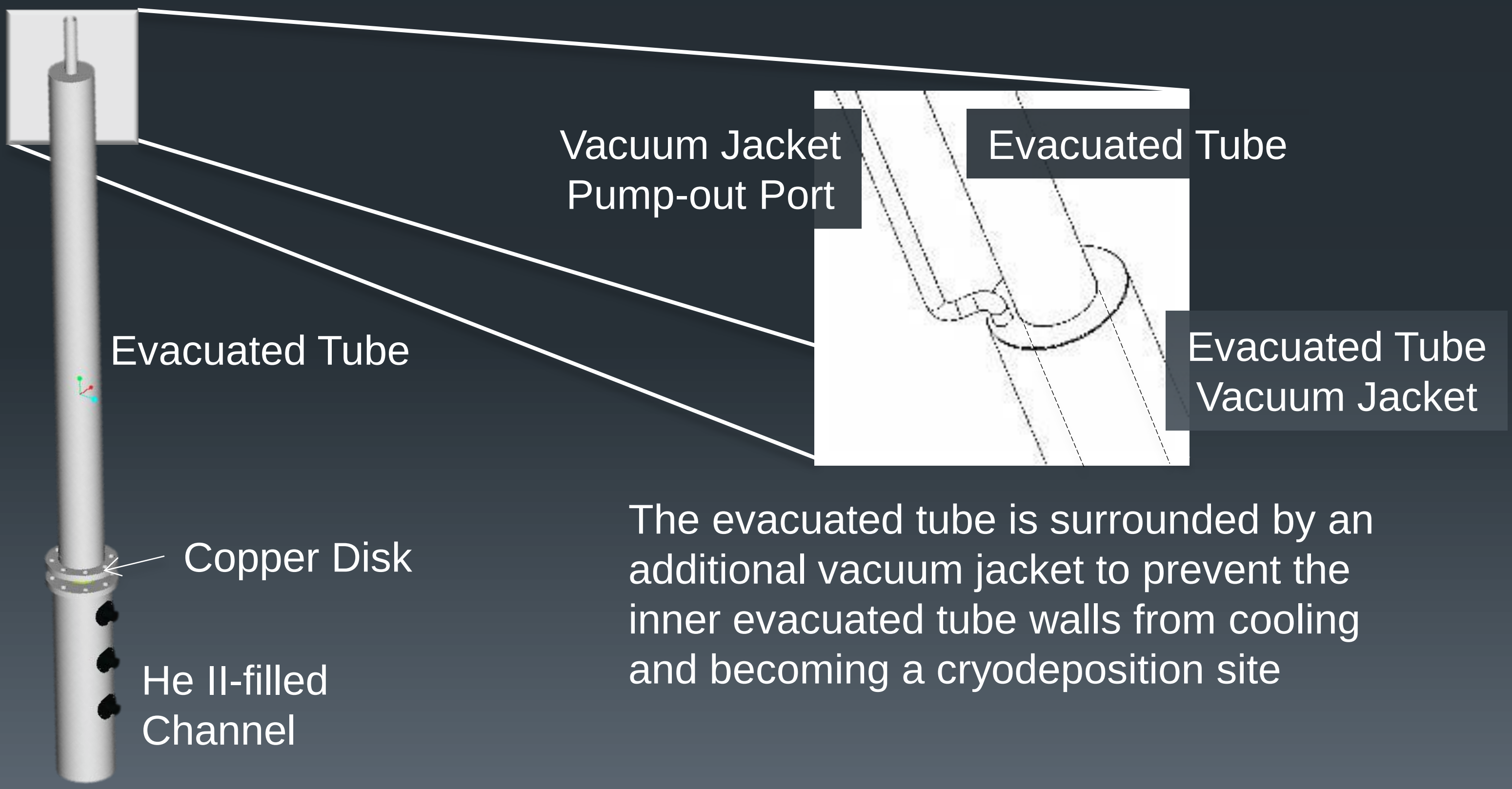
- A vacuum (< 10^{-3} Pa) is established in a tube, which sits between a solenoid valve, in the ambient laboratory space, and copper disk, which is in intimate contact with He II.
- The vacuum is broken by opening the solenoid valve, which allows room temperature nitrogen gas to flood into the evacuated space.



Simplifications and Details

Experiment built to simulate a real world vacuum failure

- Pure nitrogen gas (not air) floods into the broken vacuum
- He II Channel, Copper Disk, and Evacuated Tube share a 25.4 mm diameter to constrain all heat transfer to one dimension [axially] in space

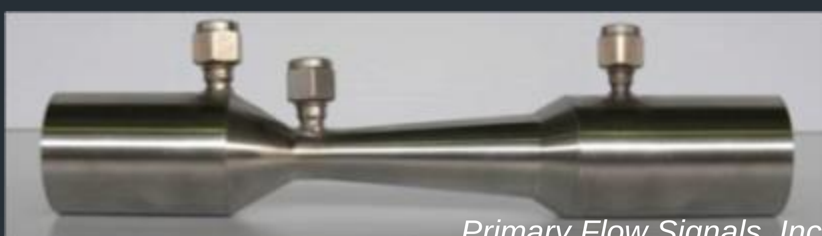


The evacuated tube is surrounded by an additional vacuum jacket to prevent the inner evacuated tube walls from cooling and becoming a cryodeposition site

Measurements

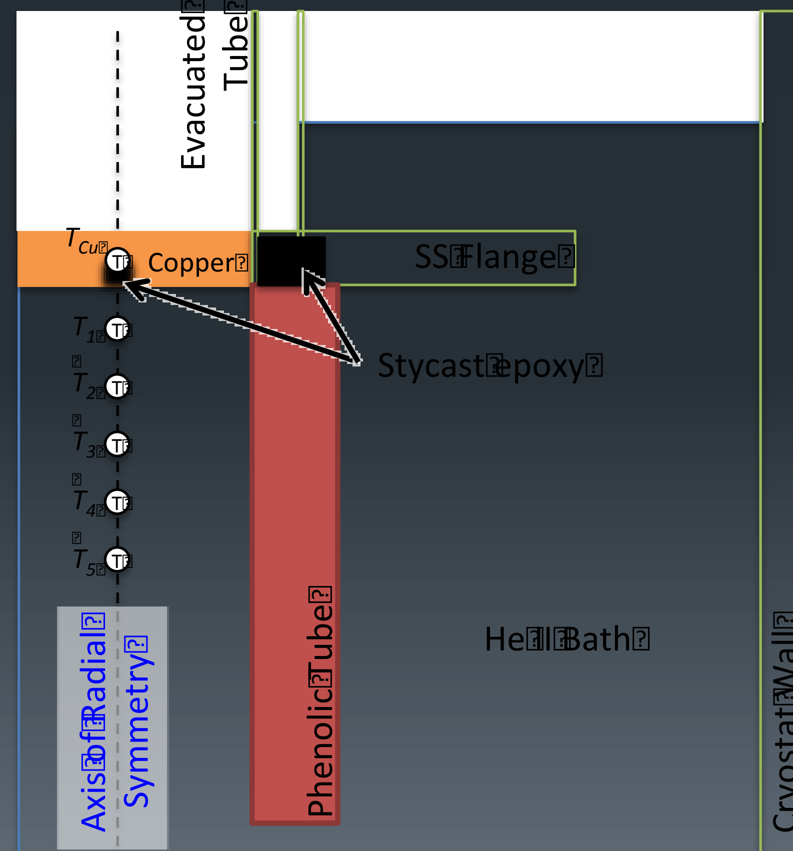
Mass flow and temperature measurements acquired

- Mass flow rate of nitrogen entering vacuum space provides a first approximation of cryodeposition rate
- Temperature traces of the copper disk and He II provide thermal gradients from which heat fluxes and heat transport modes are deduced



Primary Flow Signals, Inc

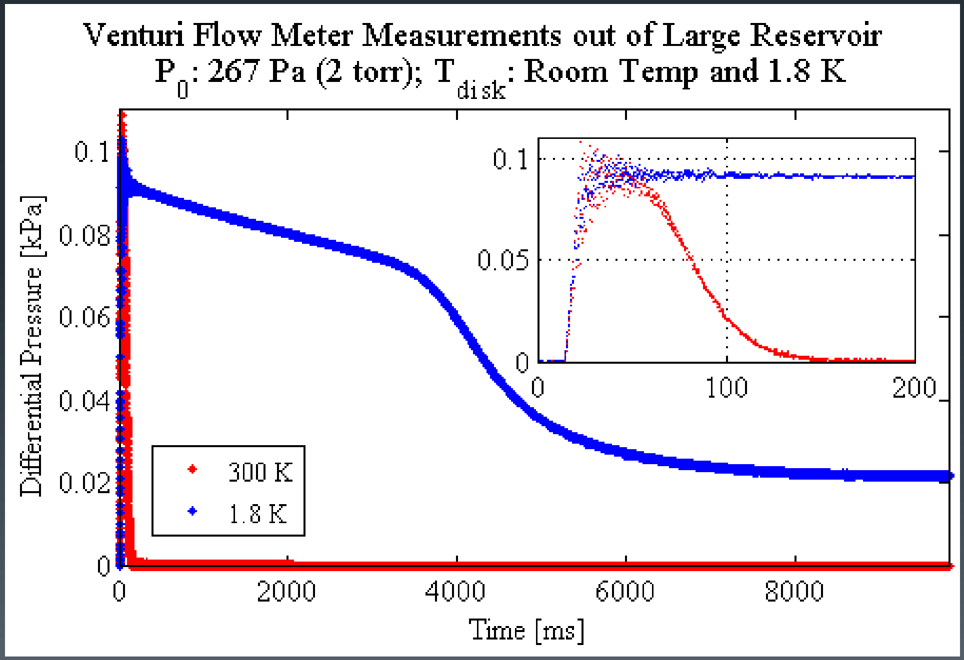
$$\dot{m} = C_d A \sqrt{\frac{2 P_1^2}{R T_1} \frac{\gamma}{\gamma - 1} \left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} \left(1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right) \left(\frac{1}{1 - \left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} \left(\frac{D_2}{D_1}\right)^4}\right)}$$

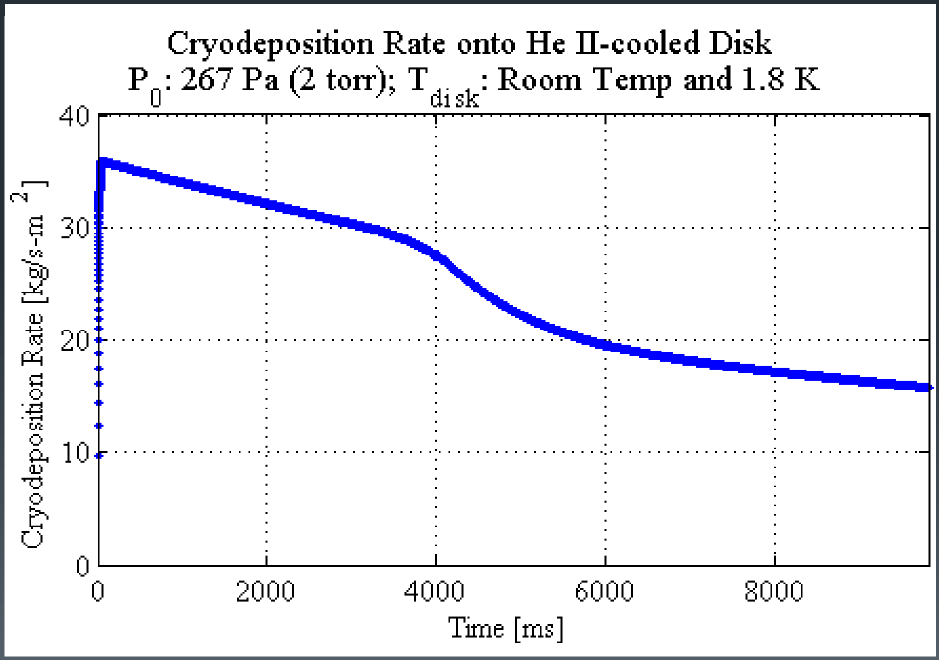


Mass Transport Observations

Experiments performed with and without He II in the cryostat
(I.e. *T_CuDisk = 1.8 K,* as well as *293 K*).

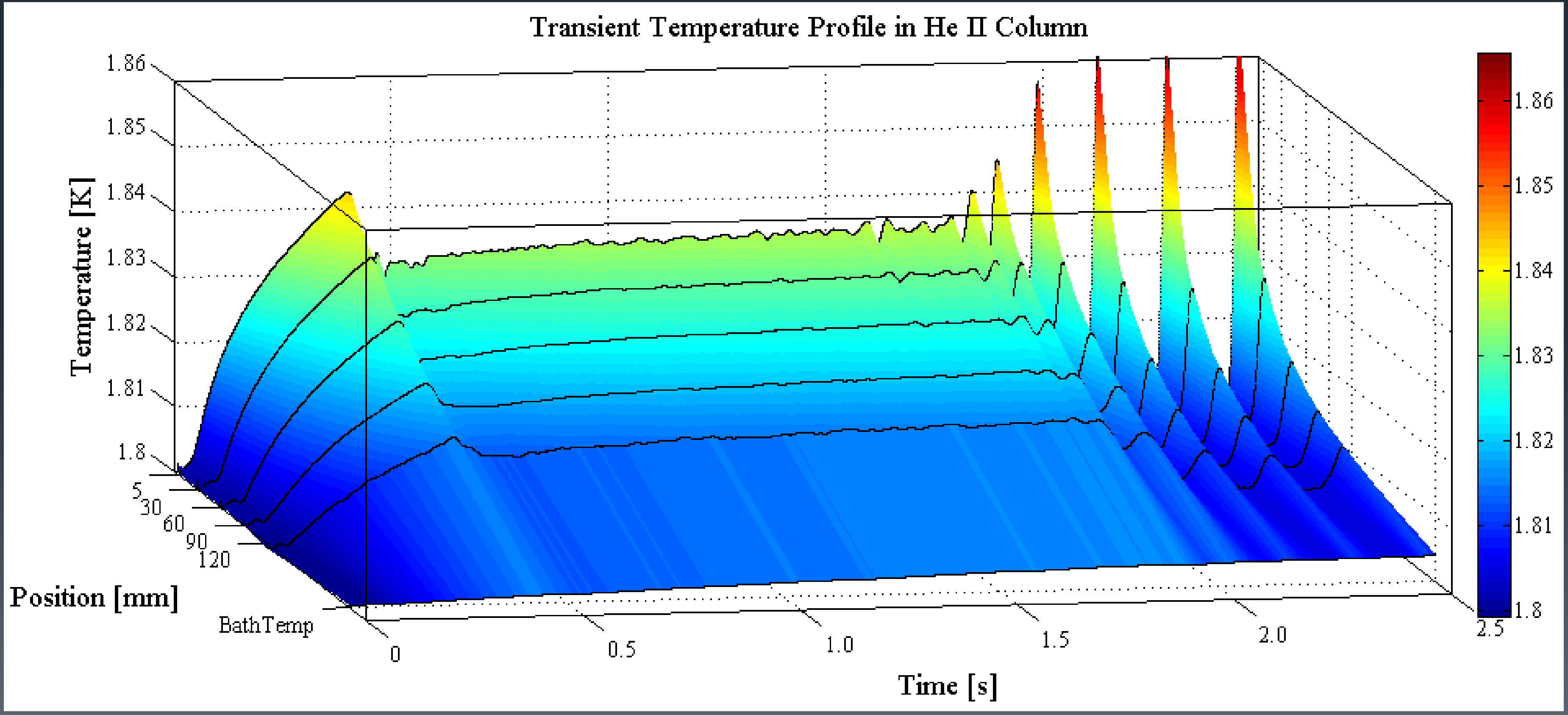
- Without He II, flow is observed to rapidly rise and fall (red line)
- With He II, flow is observed to rise identically as before but remain constant
  - The flow reaches choked conditions.in the venturi
  - Flow rate is equivalent to the cryodeposition rate.
  - Mass transfer is coupled with the heat transfer to the solid surface





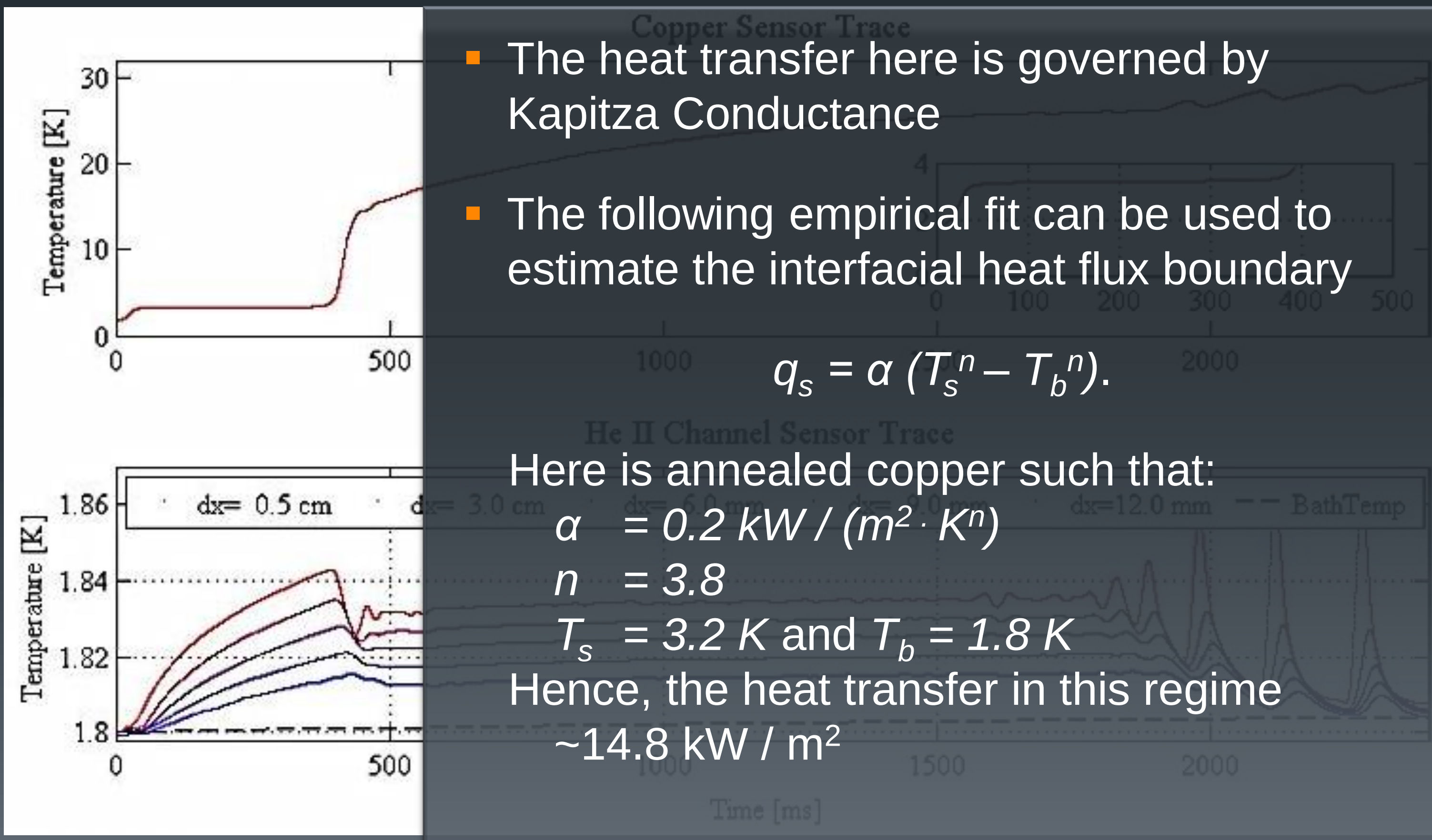
He II Heat Transport Observations

- Three distinct regimes of heat transfer to the He II
  - Kapitza Conductance regime
  - Silent Film Boiling
  - Noisy Film Boiling
- Copper disk temperature profiles coupled with He II temperatures



HT: Kapitza Conductance

- In the experiment, initial transient heating of He II is smooth
- The end of this regime is distinguished with stepped decrease and establishment of a mostly steady state thermal gradient



- The heat transfer here is governed by Kapitza Conductance
- The following empirical fit can be used to estimate the interfacial heat flux boundary

$$q_s = \alpha \, (T_s^n - T_b^n).$$

Here is annealed copper such that:

$\alpha = 0.2 \, kW / (m^2 \cdot K^n)$

$n = 3.8$

$T_s = 3.2 \, K$ and $T_b = 1.8 \, K$

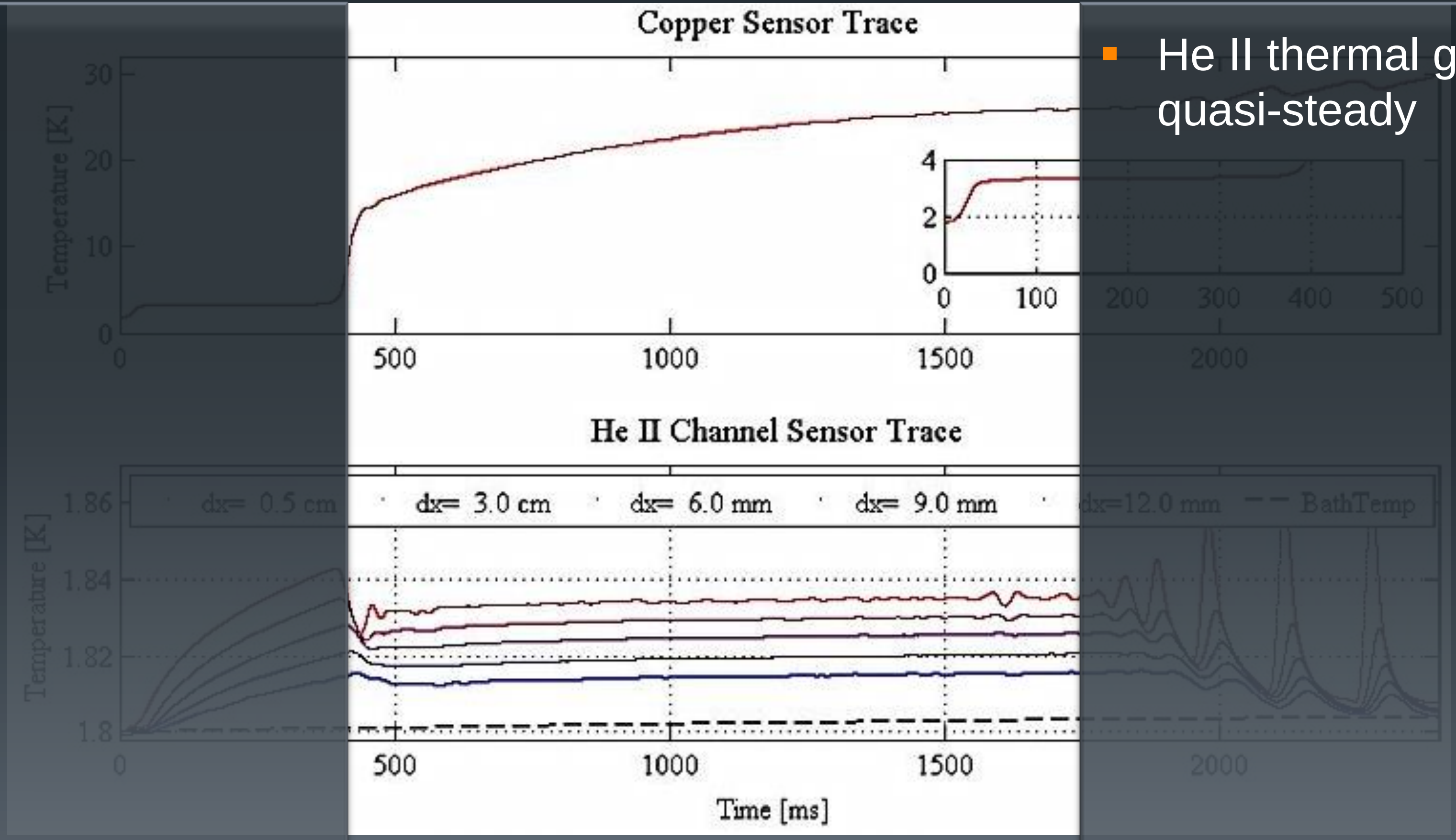
Hence, the heat transfer in this regime ~14.8 kW / m^2

HT: Silent Film Boiling

Onset of silent film boiling shows coupled thermometry data in both the copper and He II sensors:

-- a step down in thermal gradient in the He II

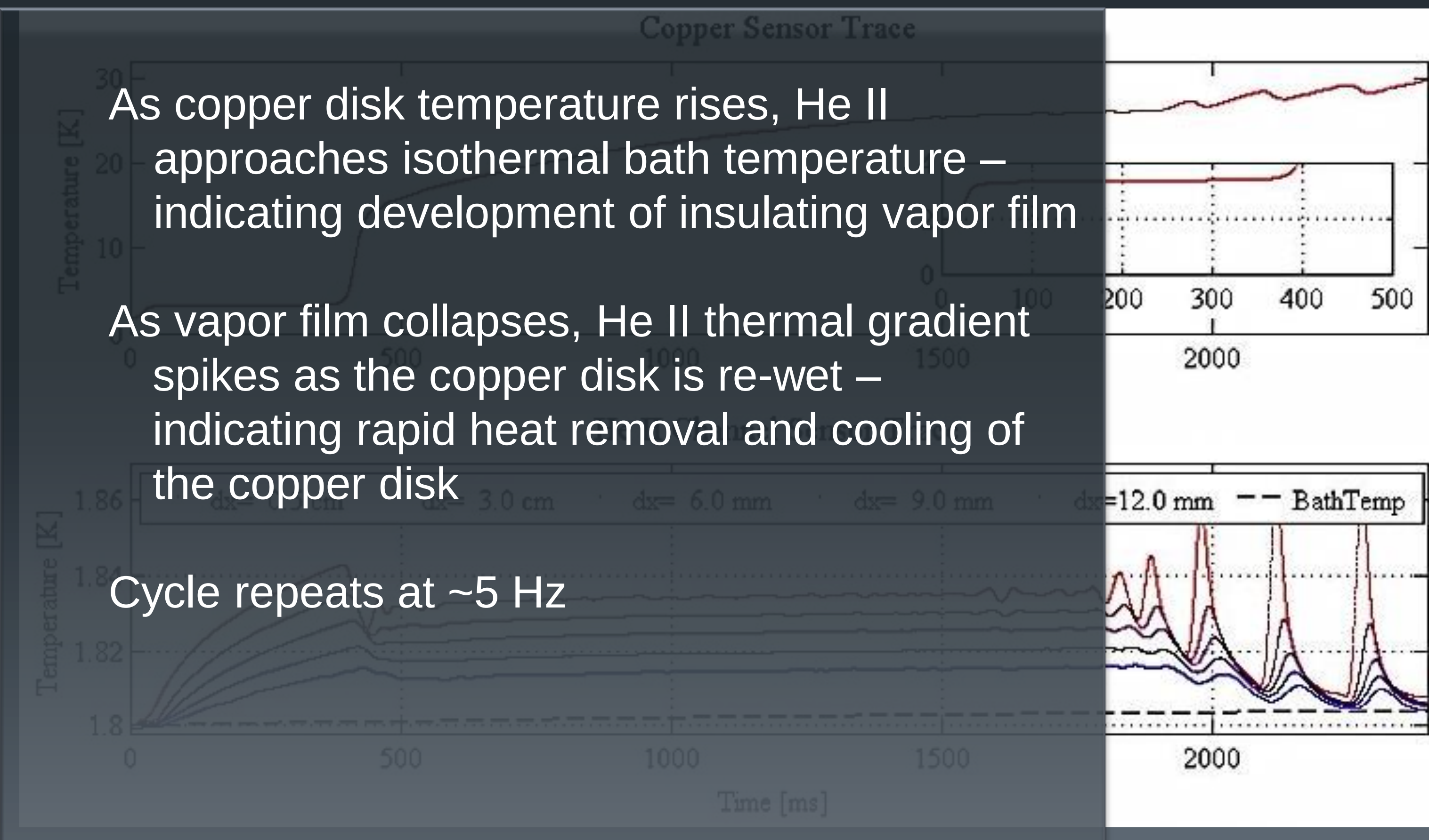
-- a sudden and sharp rise in copper disk temperature



- He II thermal gradient becomes quasi-steady

HT: Noisy Film Boiling

- Oscillations in temperature measurements indicate noisy film boiling
- Similar to silent film boiling, temperature sensors show coupled data
- Heat flux clearly lower as disk temperature allowed to generally rise



As copper disk temperature rises, He II approaches isothermal bath temperature – indicating development of insulating vapor film

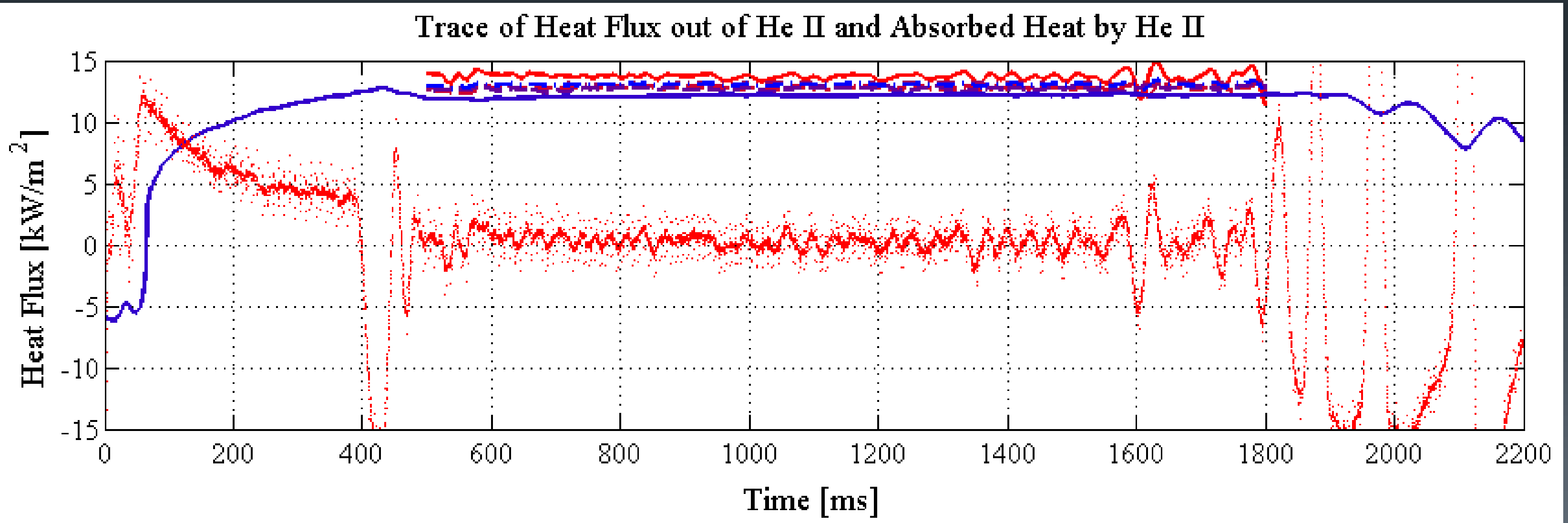
As vapor film collapses, He II thermal gradient spikes as the copper disk is re-wet – indicating rapid heat removal and cooling of the copper disk

Cycle repeats at ~5 Hz

Heat Transfer: Analysis (1 of 2)

Heat fluxes drop with onset of silent film boiling and are further reduced with the onset of noisy film boiling

- Duration of Kapitza Conductance regime shortens as flow rates increase
- Hence, substantial high heat flux can be estimated with peak heat flux theory
- Data used to determine heat absorbed into He II column and copper disk as well as the heat conducted out of the He II column
  - Absorbed heat calculated by integrating: $m \cdot c_p \cdot dT$
  - Heat conducted out of He II channel by evaluating: $[\, f^{-1}(T) \cdot dT/dx \,]^{1/3.4}$



Heat Transfer: Analysis (2 of 2)

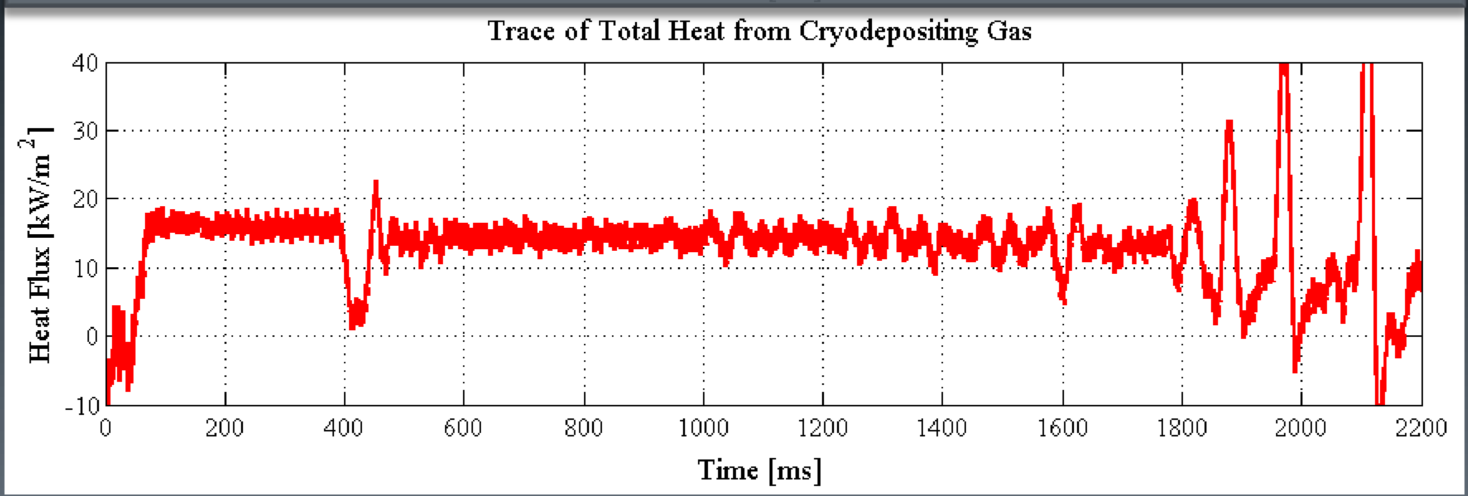
Heat absorbed by the disk is shown in grey, and the sum of the heat fluxes to the He II (absorbed and conducted out of the He II channel) are traced in black

During silent film boiling, theory predicts peak heat flux

$$q^* = \left(\frac{1}{L}\int_{T}^{T_{limit}} f^{-1}(T)\,dT\right)^{\frac{1}{3.4}}$$

Comparisons between observed and theory:

	Kapitza Conductance	Silent Film Boiling
Expected	14.8 kW / m^2	12.1 kW / m^2
Observed	16 kW / m^2	13 kW / m^2



Summary

- Heat transfer during Sudden Catastrophic Loss of Vacuum in a saturated He II cooled system goes through multiple stages