A new type of mixing chamber for a zero gravity dilution refrigerator

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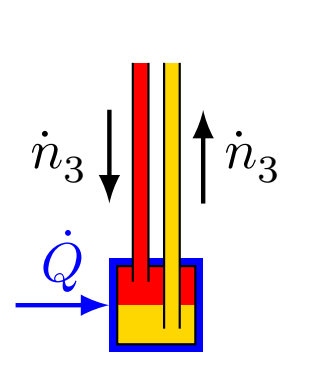
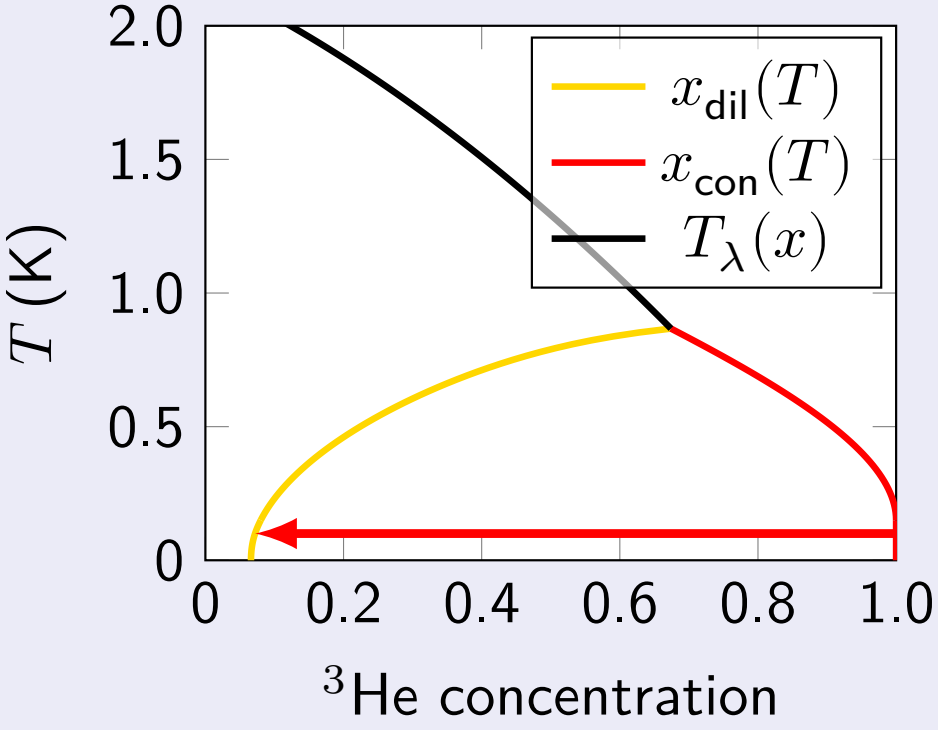
Outline

1. ^{3}He-^{4}He Dilution Refrigeration Crash Course
2. Experimental Setup
3. Thermodynamic Results
4. Thermal contact
5. Conclusion

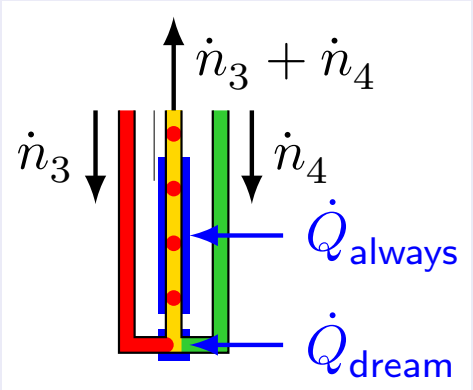
^{3}He-^{4}He dilution refrigeration on EARTH and in SPACE

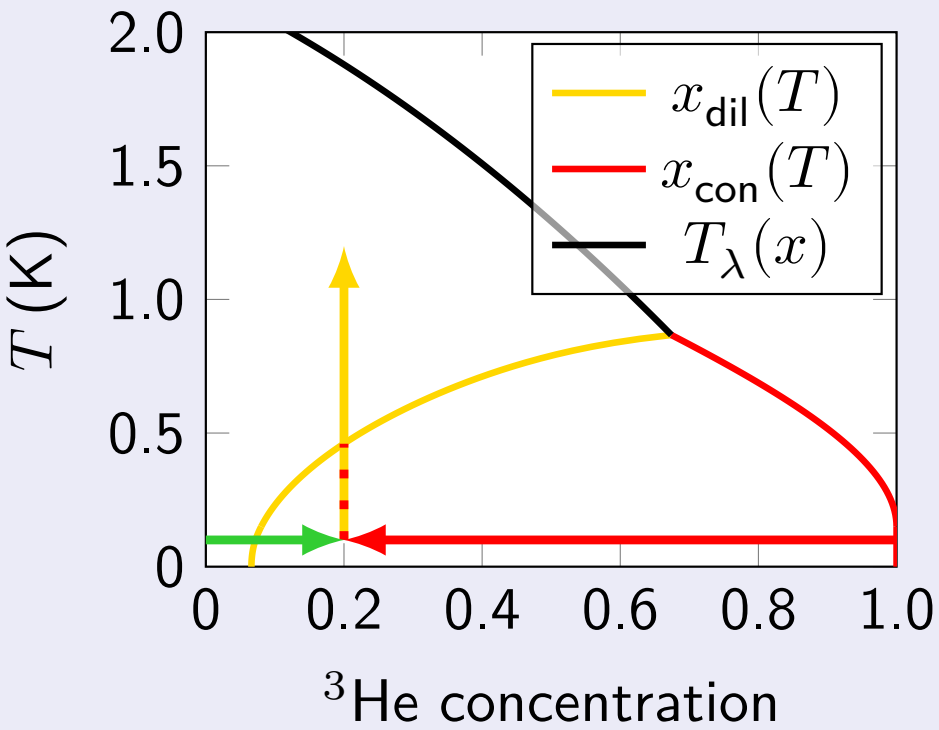
Gravity important on EARTH





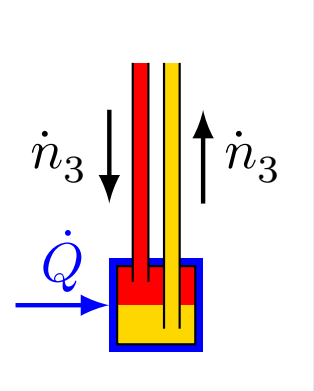
Capillarity takes over in SPACE



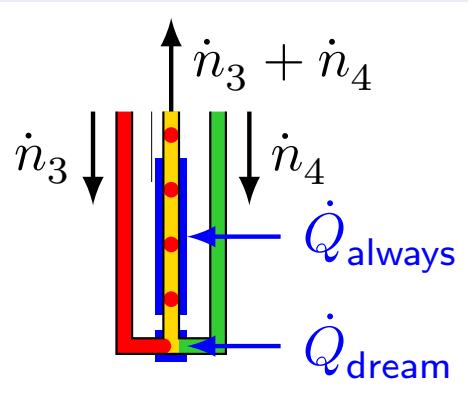


^{3}He-^{4}He dilution refrigeration on EARTH and in SPACE

EARTH



SPACE



^{3}He-^{4}He dilution thermodynamics

- ✔ mixture thermodynamics
- ✘ superfluid ^{4}He constraints
  - ✔ nearly 50 % of cooling power

^{3}He-^{4}He dilution refrigeration on EARTH and in SPACE

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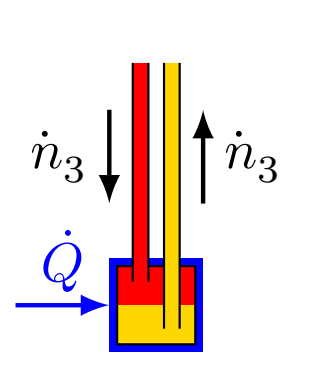

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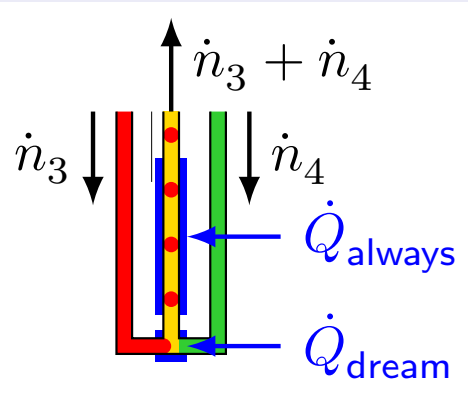

^{3}He-^{4}He dilution thermodynamics

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Superfluidity: stationary state and small $\vec{v}_{\text{superfluid}}$

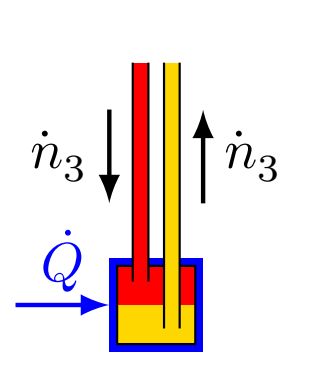
- ^{4}He chemical potential acts only on superfluid:

$$\frac{\partial \vec{v}_{\text{superfluid}}}{\partial t} = -\nabla \mu_4(p, T, x) = 0$$

- use ^{3}He droplets or turbulence for $\nabla \mu_4 \neq 0$

^{3}He-^{4}He dilution refrigeration on EARTH and in SPACE

EARTH



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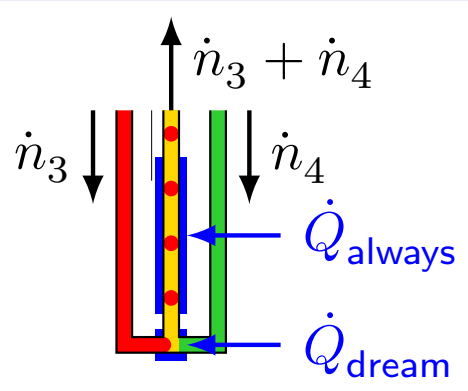

^{3}He-^{4}He dilution thermodynamics

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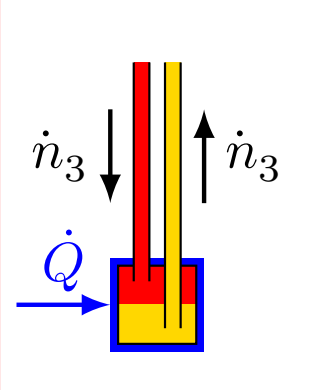
Enthalpy balance: $\dot{n}_{\text{flow}} h_{\text{flow}}$ in dilute ^{3}He-^{4}He?

- is $\nabla \mu_4(p, T, x) = 0$?
- what is moving and what is at rest?

	EARTH		SPACE	
state	^{3}He	^{4}He	^{3}He	^{4}He
at rest		✔	✔	
moving	✔		✔	✔

First Law of Thermodynamics and Chaudhry's Rule

Earth



First Law of Thermodynamics ($dU/dt = \dot{W} = 0$)

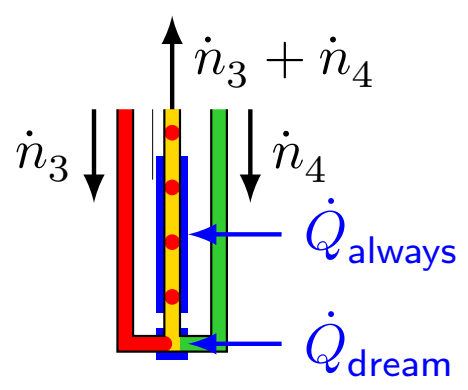
$$\frac{dU}{dt} = \dot{Q} - \dot{W} + \sum_{\text{ports}} \dot{n}_{\text{flow}} h_{\text{flow}}(T, x)$$

$\dot{Q}$ is heat transfer rate into system

$\dot{W}$ is work transfer rate from system

First Law of Thermodynamics and Chaudhry's Rule

Space



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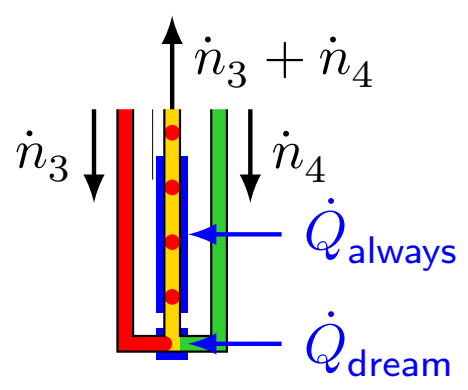

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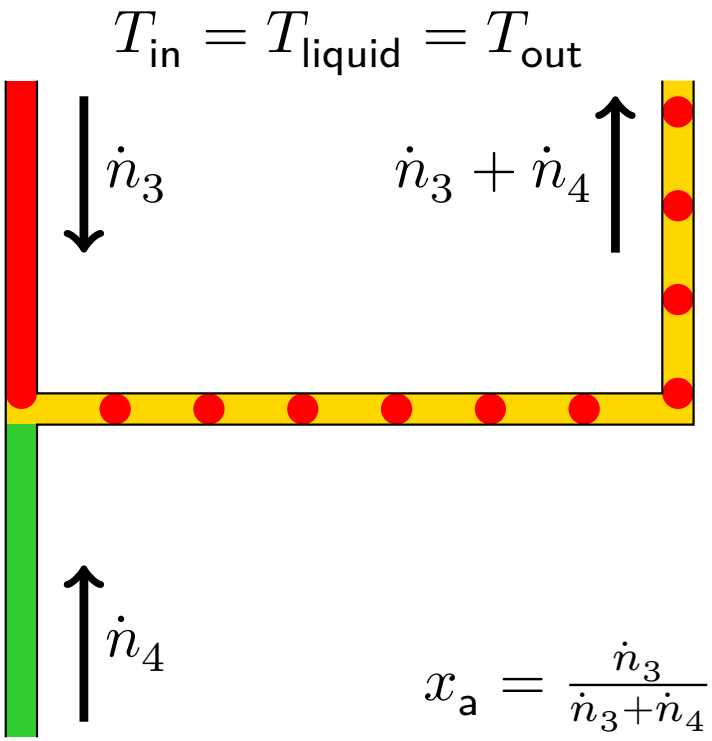
Chaudhry's rule for dilute (skip concentrated) ^{3}He-^{4}He mixtures

$$\sum_{\text{ports}} \dot{n}_{\text{flow}} h_{\text{flow}}(T, x) = \sum_{\text{ports}} \dot{n}_3 h_{\text{osmotic}}(T, x) + \sum_{\text{ports}} \dot{n}_4 \mu_4(T, x),$$

$$\text{where } h_{\text{osmotic}}(T, x) \equiv \frac{h_{34}(T, x) - (1 - x)\mu_4(T, x)}{x}$$

$$\dot{Q} = -\sum_{\text{ports}} \dot{n}_3 h_{\text{osmotic}}(T, x) - \sum_{\text{ports}} \dot{n}_4 \mu_4(T, x) - \sum_{\text{ports}} \text{concentrated}$$

Old to new mixing chamber idea

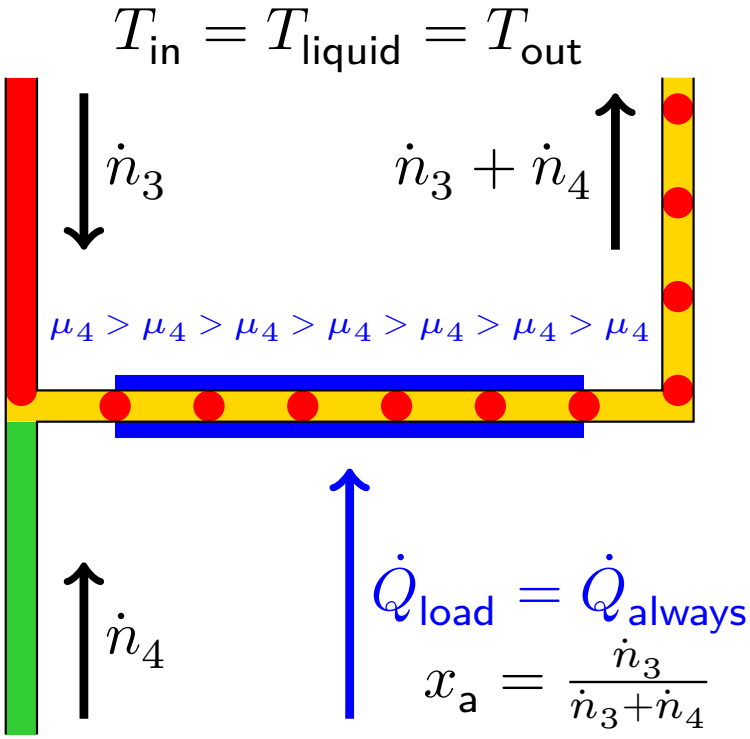


Thermodynamics from old to new design

1. perfect CFHX: $\dot{n}_{3,\text{con}} h_{30}(T_{\text{liquid}})$

Enthalpy balance

Old to new mixing chamber idea



Thermodynamics from old to new design

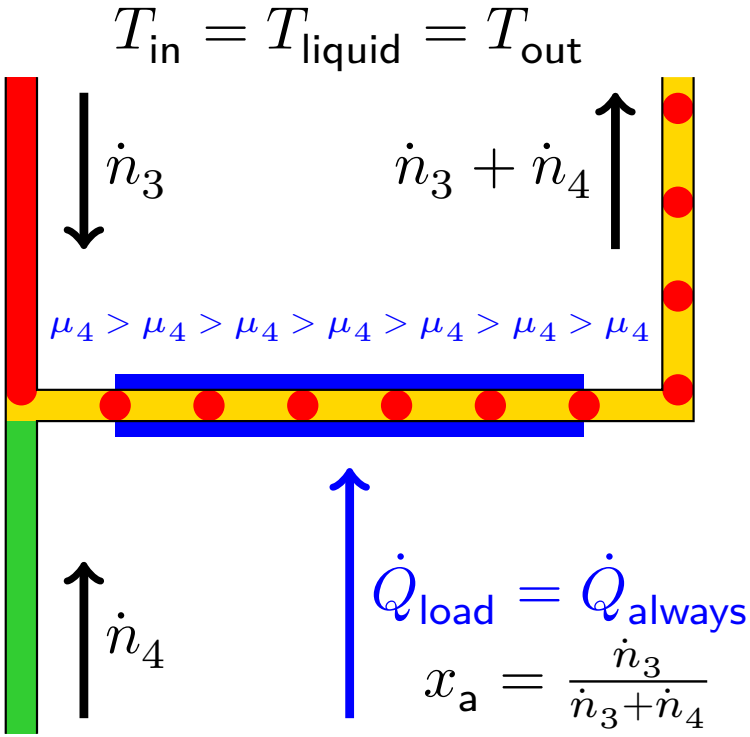
1. perfect CFHX: $\cancel{\dot{n}_{3,\text{con}} h_{30}(T_{\text{liquid}})}$
2. Planck-like thermal anchor design

Enthalpy balance

$$\dot{Q}_{\text{load}} = \dot{n}_{3,\text{dil}}[h_{\text{osmotic}}(T_{\text{liquid}}) - h_{30}(T_{\text{liquid}})] \qquad + \dot{n}_4[\mu_4(T_{\text{liquid}}) - \mu_4(T_{\text{mc}})]$$

use: $\dot{n}_{3,\text{dil}} = \dfrac{x_{\text{dil}}(T_{\text{liquid}})}{1 - x_{\text{dil}}(T_{\text{liquid}})} \dot{n}_4$

Old to new mixing chamber idea



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$$\frac{\dot{Q}_{\text{load}}}{\dot{n}_4} \approx 5.33 T_{\text{liquid}}^2 \quad -2.31 T_{\text{liquid}}^2$$

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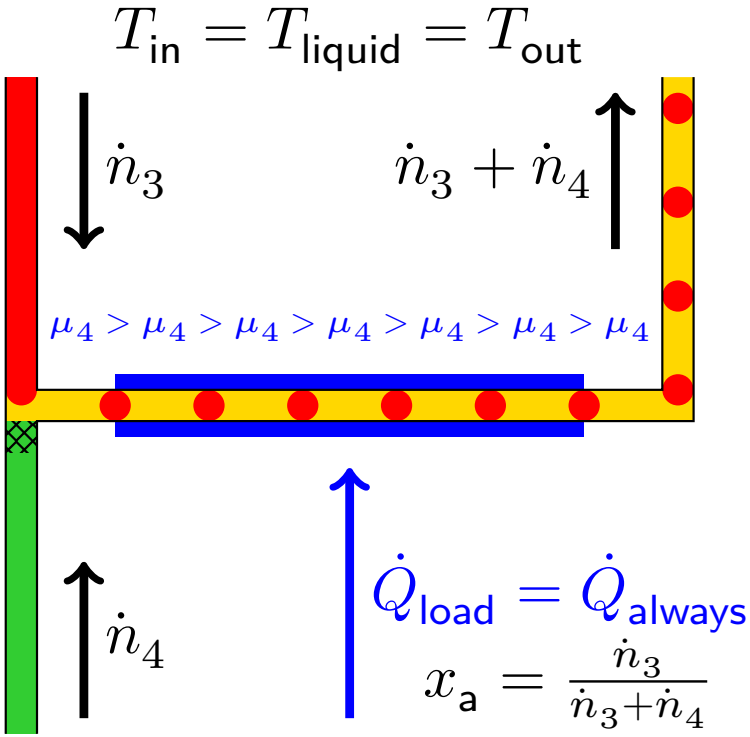

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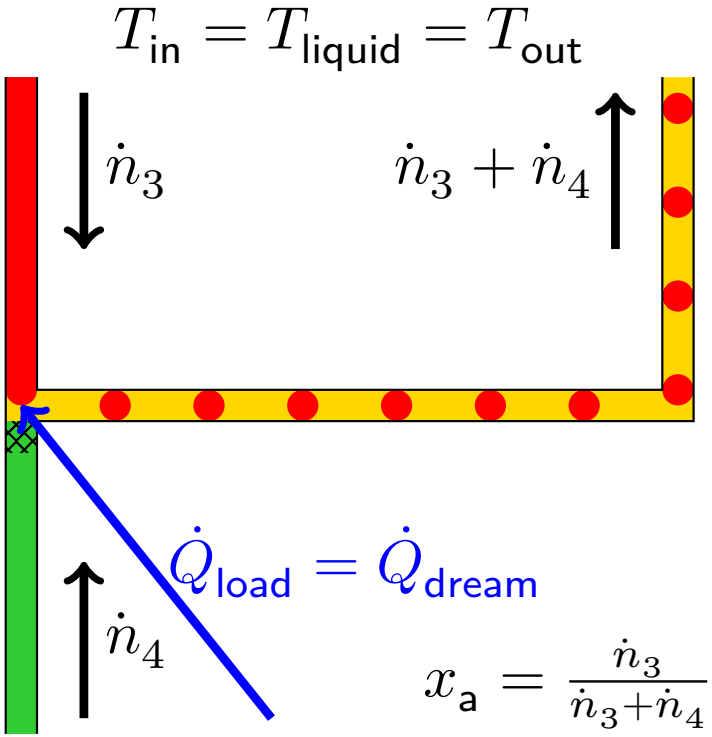

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4. more cooling power if $\dot{Q}_{\text{load}} = \dot{Q}_{\text{dream}}$

Enthalpy balance

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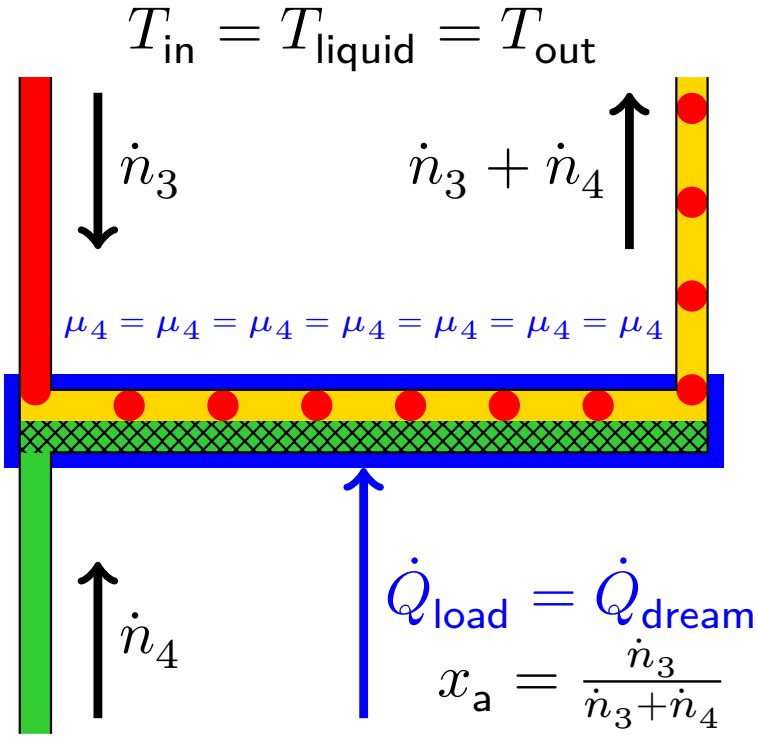

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5. $-\nabla\mu_4 = 0$ with open parallel superleak
   - silver sinter superleak for better HX

Enthalpy balance

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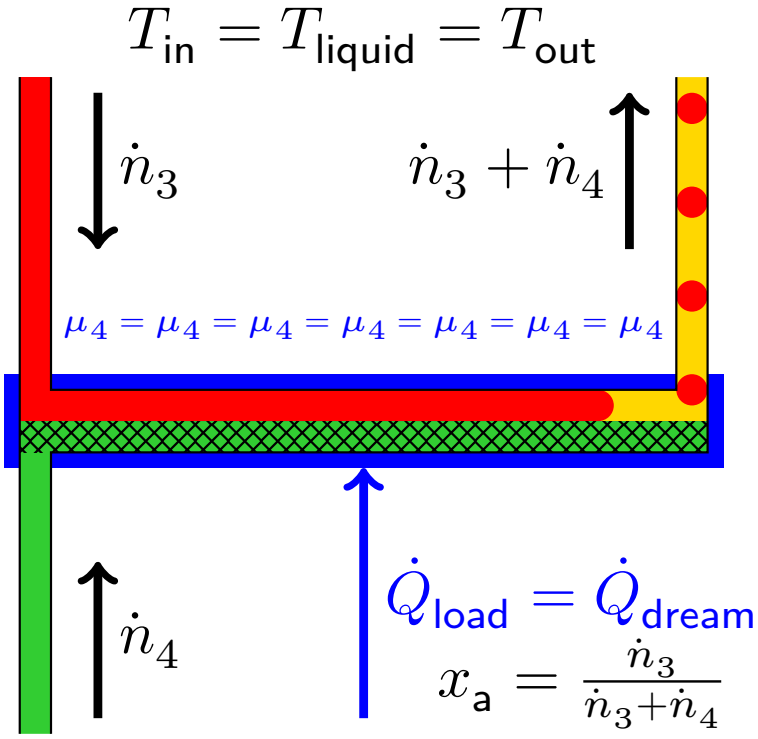

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   - silver sinter superleak for better HX
6. flow inside? same thermodynamics

Enthalpy balance

$$\frac{\dot{Q}_{\text{load}}}{\dot{n}_4} = \frac{x_{\text{dil}}(T_{\text{liquid}})}{1 - x_{\text{dil}}(T_{\text{liquid}})}\left[h_{\text{osmotic}}(T_{\text{liquid}}) - h_{30}(T_{\text{liquid}})\right] \quad \cancel{+\left[\mu_4(T_{\text{liquid}}) - \mu_4(T_{\text{mc}})\right]}$$

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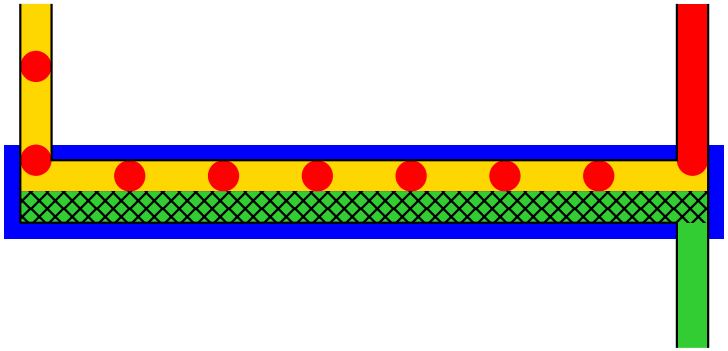
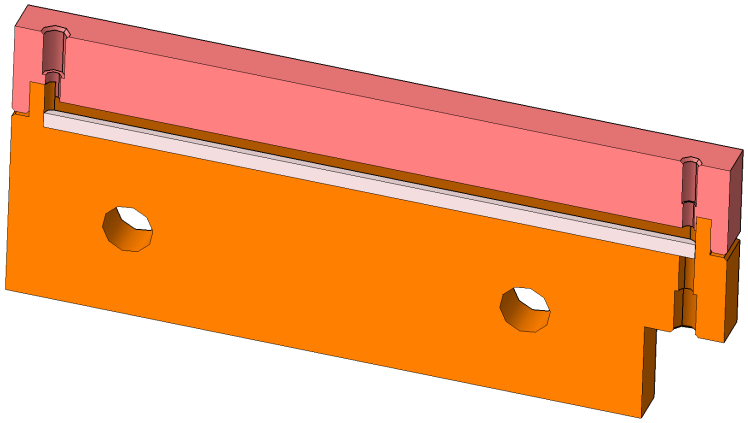
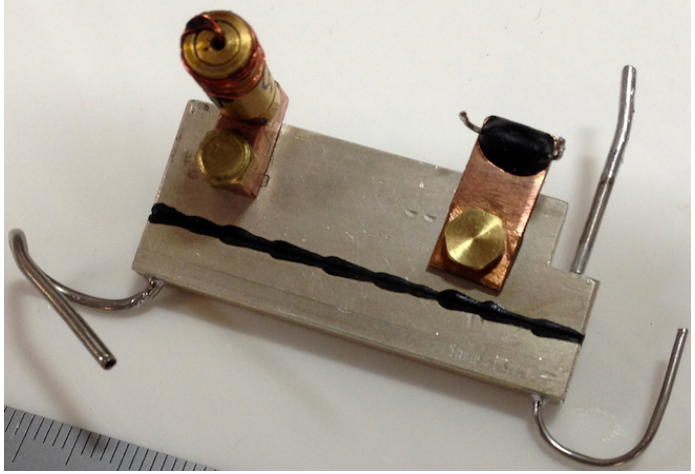
New mixing chamber design and assembly







Design objectives and final assembly

- ✔ simple construction
- ✔ force ^{4}He flow through sinter
- ✔ superleak properties: $\nabla\mu_4 = 0$
  - Ag powder size of $(40-90)$ nm
  - Tohuriki Honten C-34 powder
- ✘ thick sinter: no optimal heat exchange
  - 40 mm $\times$ 1 mm $\times$ 1 mm sinter
- ✘ keep round ^{3}He-^{4}He mixture capillary
  - 40 mm $\times$ 1 mm $\times$ 1 mm channel
- ✔ housing: easy to machine and to sinter
  - coin silver 950 (95 % Ag)
- ✔ close with Stycast 2850 FT epoxy
  - do not overheat sinter
- ✔ choose size compatible with test setup

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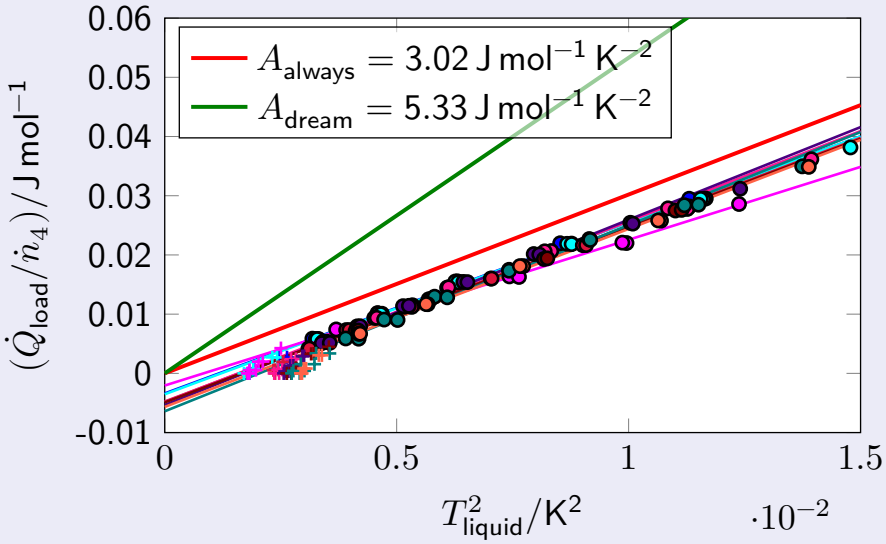
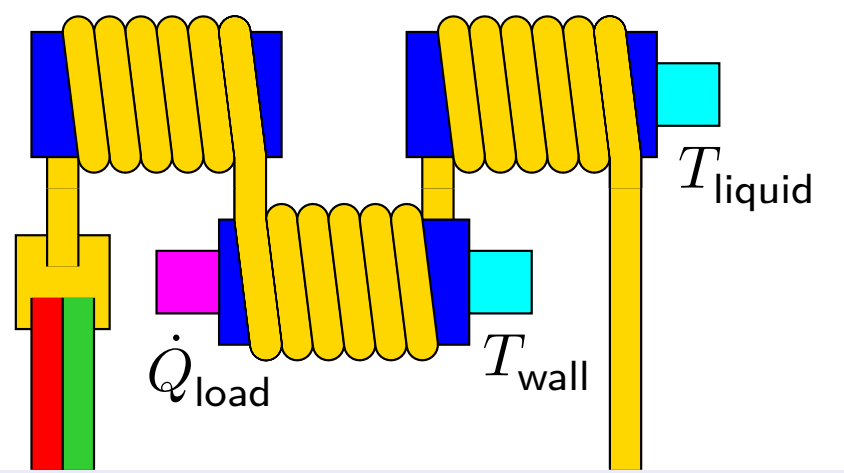
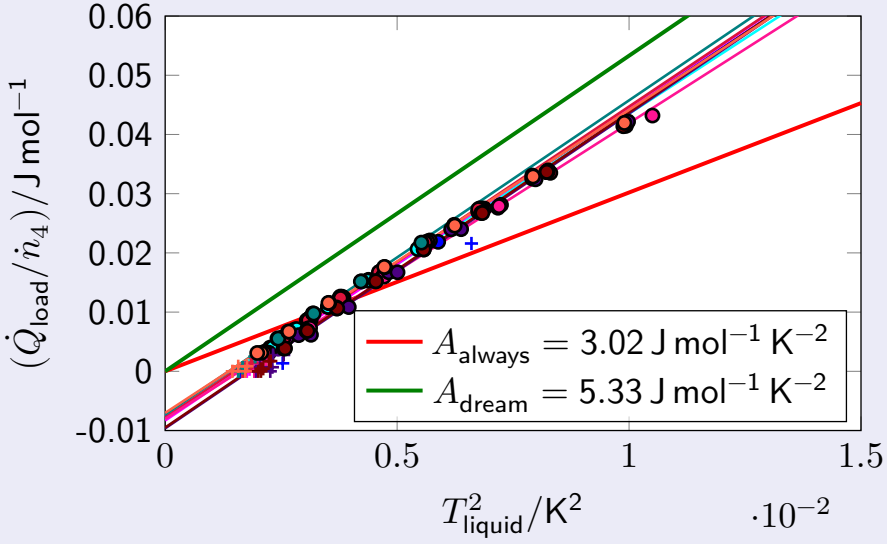
Comparing and fitting the thermodynamic data

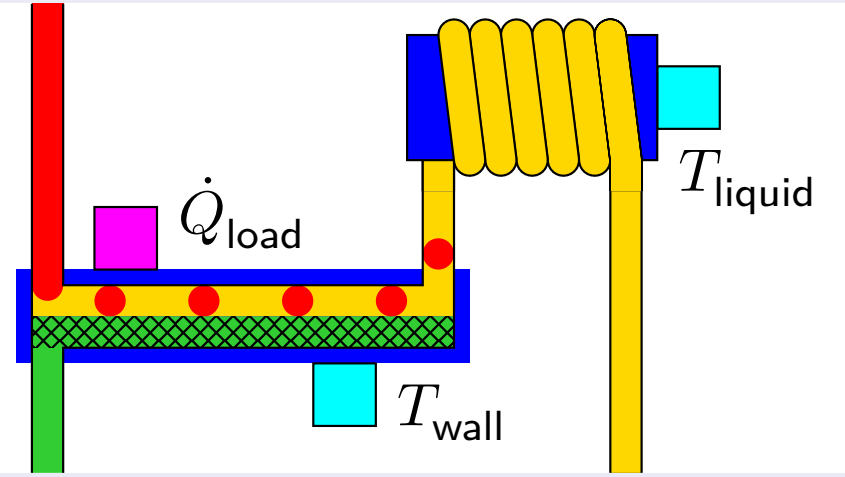
Old always setup Planck-like data





New dream setup silver sinter data





Comparing and fitting the thermodynamic data

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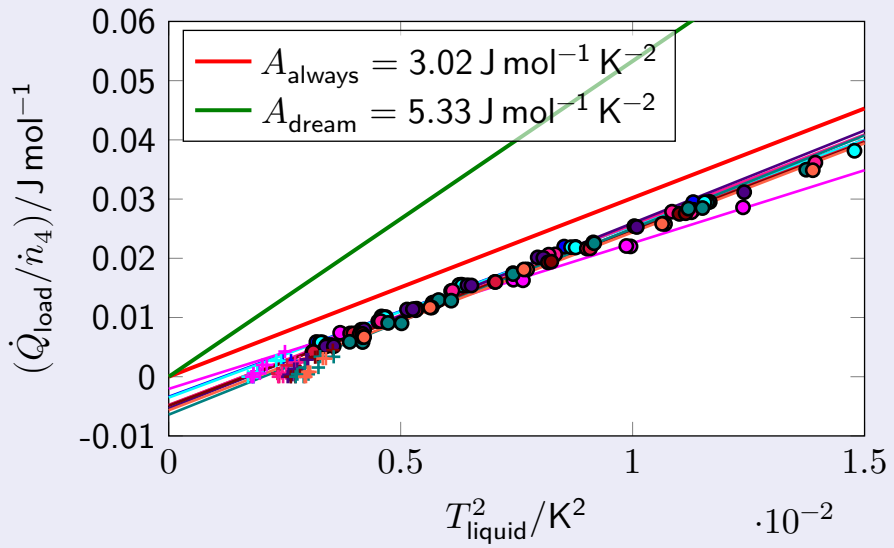

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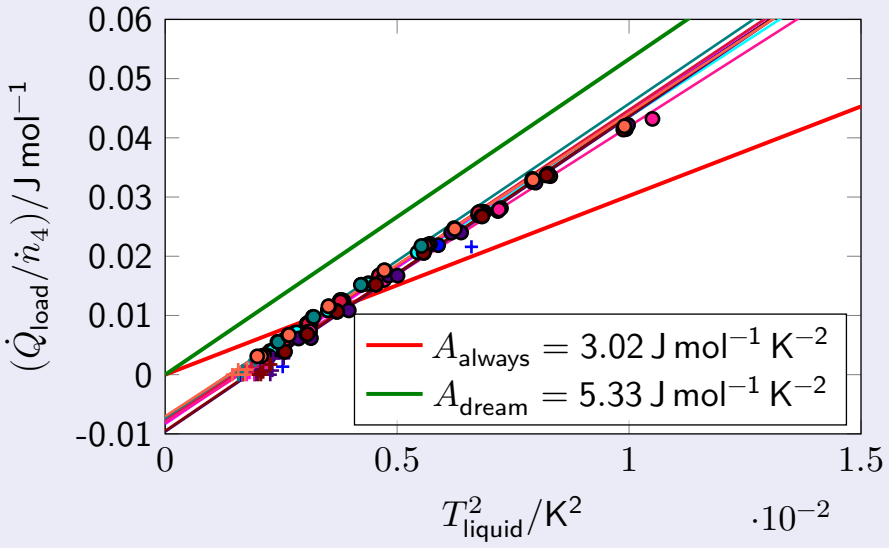

Average A values in $\dot{Q}_{\text{load}} = \dot{n}_4 A T^2_{\text{liquid}}$ using $\dot{Q}_{\text{FP}} = \dot{n}_4 T_{\text{FP}} s_{40}(T_{\text{FP}})$

setup	$A_{\text{theory}}/\text{J mol}^{-1}\,\text{K}^{-2}$	$A_{\text{data}}/\text{J mol}^{-1}\,\text{K}^{-2}$	agree
old always	3.02	2.95 ± 0.19	✔
new dream	5.33	5.20 ± 0.11	✔

at $T_{\text{FP}} = 2\,\text{K}$: $0.5\,\%$ error in T_{FP} implies $3\,\%$ error in $\dot{n}_4$

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^{3}He-^{4}He thermal conductivity limited Kapitza heat transfer

Cousins et al, PRL 73, 2583

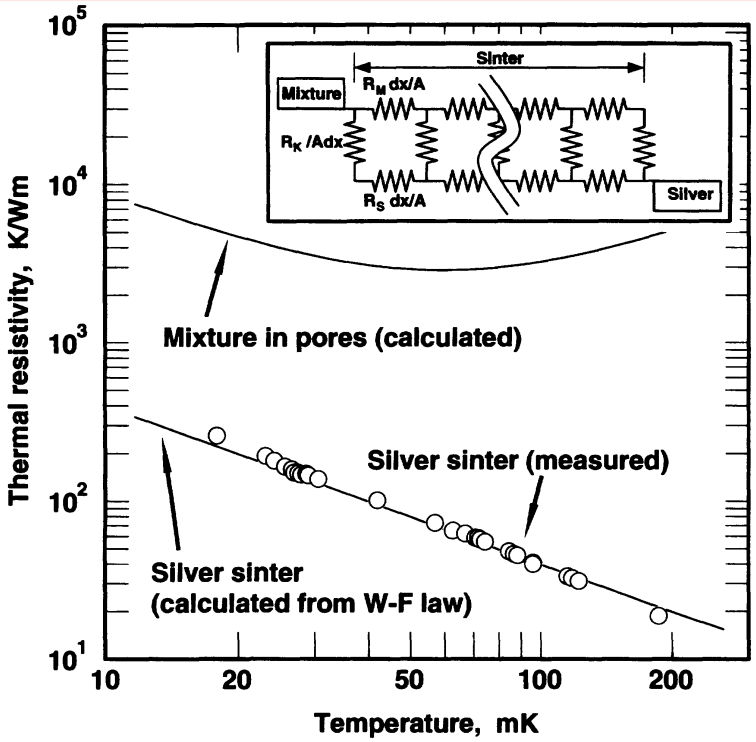


FIG. 3. The calculated thermal resistivity of a saturated dilute mixture confined within the pores of the sinter (see text), along with the measured and calculated resistivity of the silver sinter. Inset is the equivalent circuit used to model the thermal behavior.

thermal penetration length

$$\Lambda = \sqrt{k_\mathsf{M} r_\mathsf{KV} T_\mathsf{S}^{-3}}$$

Approach

- mixture conductibility k_M constant
- $k_\mathsf{S} \gg k_\mathsf{M} \implies T_\mathsf{SINTER} = T_\mathsf{S}$ constant
- volume Kapitza: $\dot{Q}_\mathsf{KV} = \frac{V}{r_\mathsf{KV}} \int T^3 dT$
- Kapitza $\dot{q}_\mathsf{KV}$ changes mixture $\dot{q}_\mathsf{M}$

$$\frac{\partial \dot{q}_\mathsf{M}}{\partial x} = \dot{q}_\mathsf{KV}(T_\mathsf{S}, T_\mathsf{M})$$

$\dot{Q}$ prefers paths of lowest R

- where are the R bottlenecks?
  - Kapitza resistance at low T_S
    - whole sinter is effective
  - liquid resistance at high T_S
    - thin sinter layer is effective
- $\implies$ exact solution of simplest model differential equation

^{3}He-^{4}He thermal conductivity limited Kapitza heat transfer

Cousins et al, PRL 73, 2583

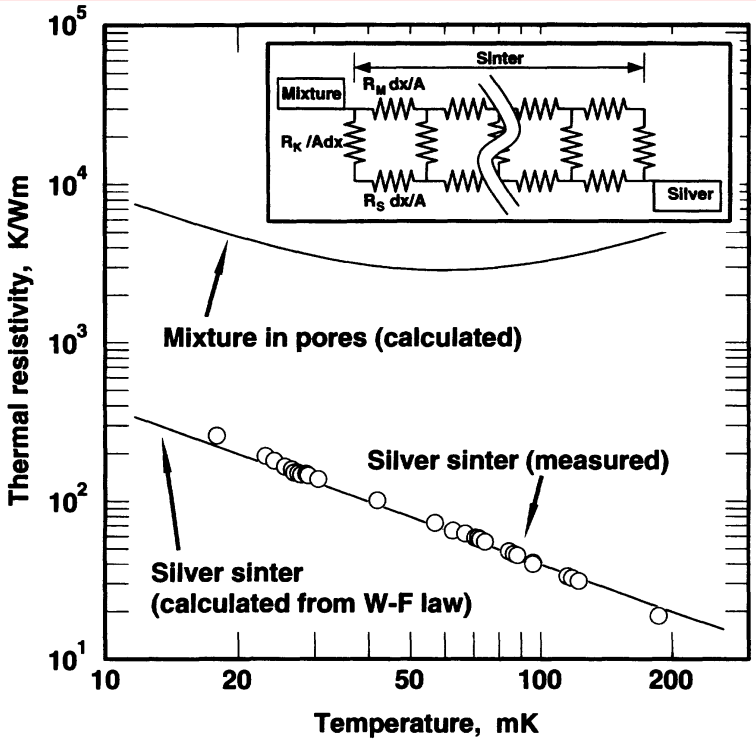


FIG. 3. The calculated thermal resistivity of a saturated dilute mixture confined within the pores of the sinter (see text), along with the measured and calculated resistivity of the silver sinter. Inset is the equivalent circuit used to model the thermal behavior.

thermal penetration length

$$\Lambda = \sqrt{k_\mathsf{M} r_\mathsf{KV} T_\mathsf{S}^{-3}}$$

Approach

- mixture conductibility k_M constant
- $k_\mathsf{S} \gg k_\mathsf{M} \implies T_\mathsf{SINTER} = T_\mathsf{S}$ constant
- volume Kapitza: $\dot{Q}_\mathsf{KV} = \frac{V}{r_\mathsf{KV}} \int T^3 dT$
- Kapitza $\dot{q}_\mathsf{KV}$ changes mixture $\dot{q}_\mathsf{M}$

$$\frac{\partial \dot{q}_\mathsf{M}}{\partial x} = \dot{q}_\mathsf{KV}(T_\mathsf{S}, T_\mathsf{M})$$

small $T_S - T_M$ and infinite thick sinter

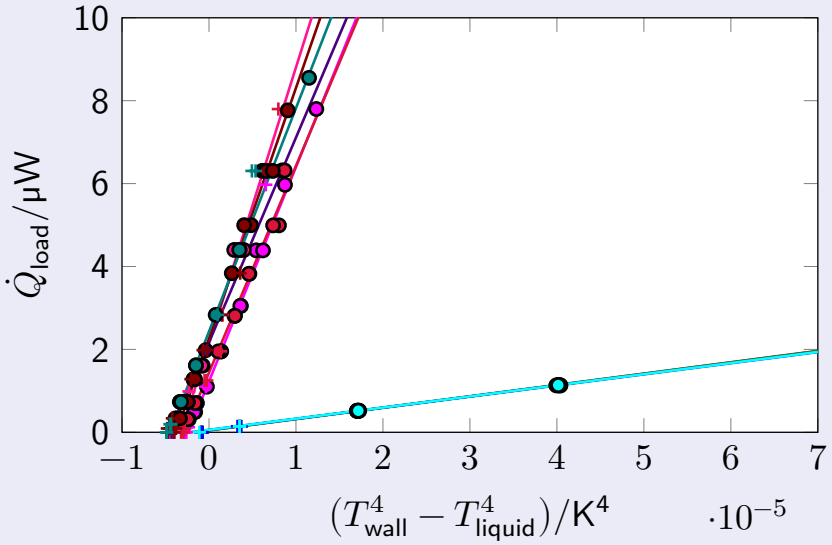
$\implies A\dot{q} = \dot{Q}$ from sinter into bulk liquid

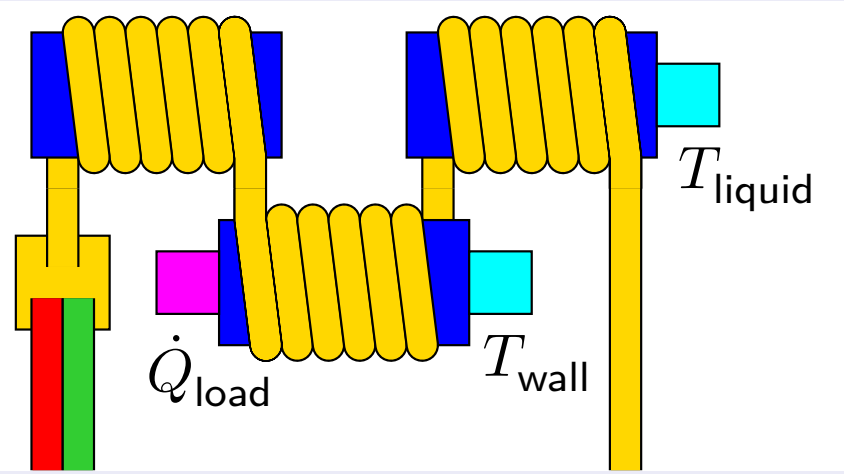
$$\dot{Q} = A\sqrt{\frac{k_M}{r_{KV}}} T_\mathsf{S}^{3/2}(T_\mathsf{S} - T_\mathsf{M}),$$

where $A = 40\,\mathrm{mm} \times 1\,\mathrm{mm}$ in our setup

Comparing and fitting the heat transfer data

Old always setup Planck-like data

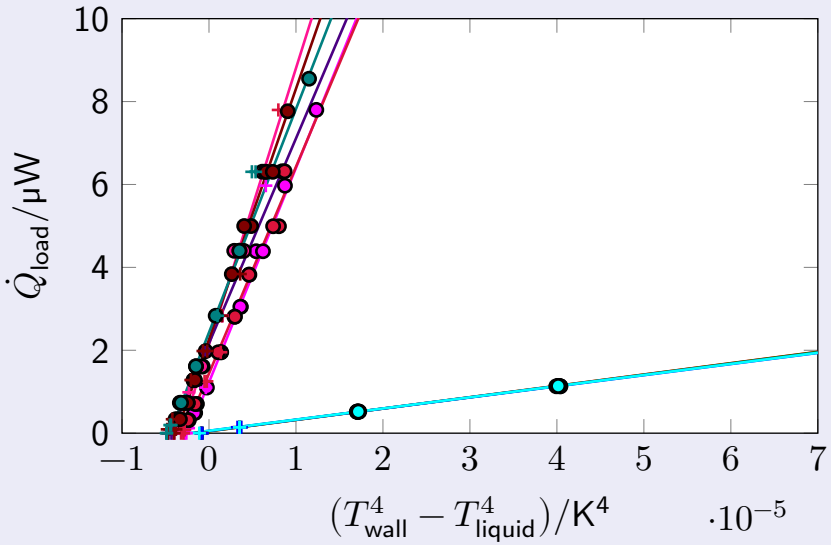




New dream setup silver sinter data

Comparing and fitting the heat transfer data

Old always setup Planck-like data

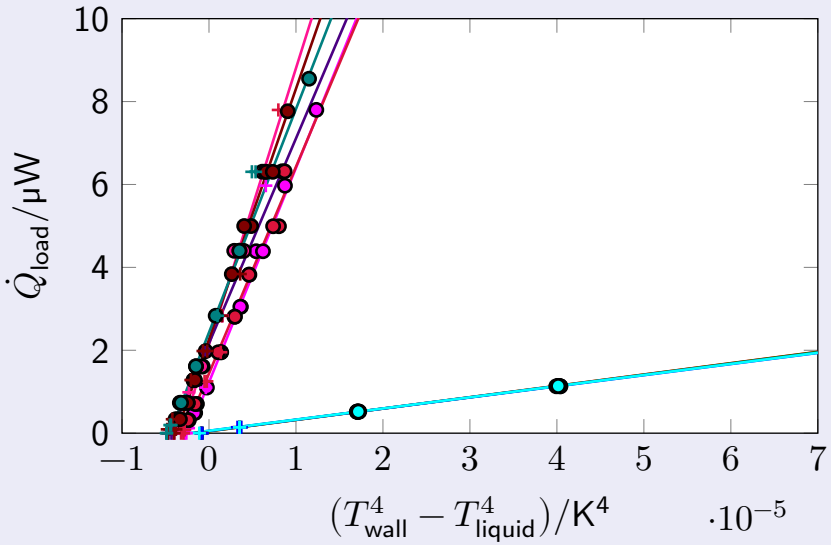


- old setup
  - ✔ $\dot{Q}_{\text{load}} \propto T^4_{\text{wall}} - T^4_{\text{liquid}}$

New dream setup silver sinter data

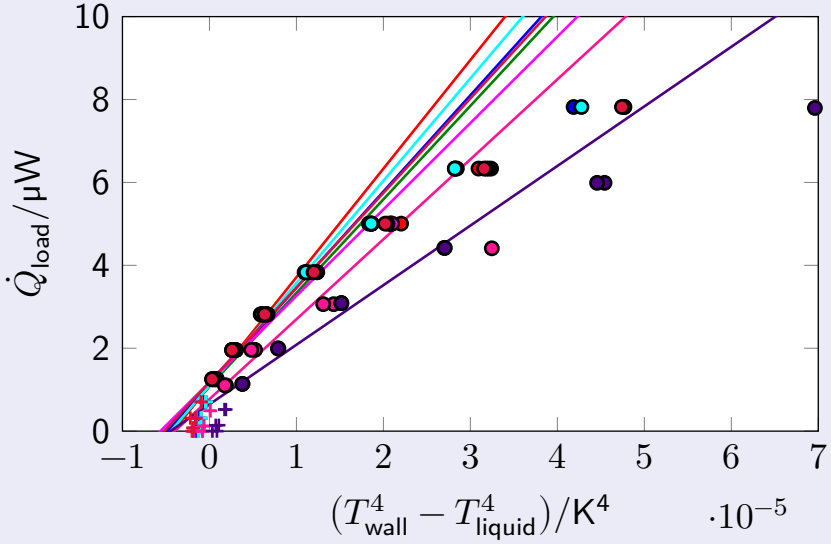
Comparing and fitting the heat transfer data

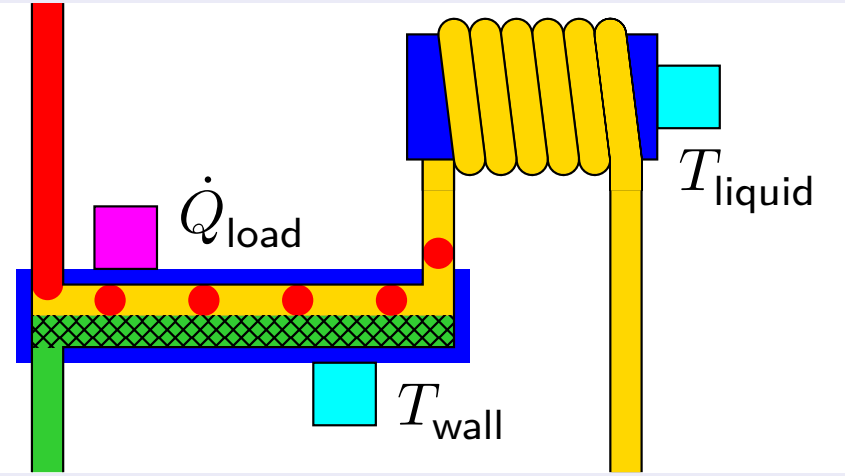
Old always setup Planck-like data



- old setup
  - ✔ $\dot{Q}_{\text{load}} \propto T^4_{\text{wall}} - T^4_{\text{liquid}}$
- new setup ($T_{\text{wall}} = T_{\text{SINTER}}$)
  - ✘ $\dot{Q}_{\text{load}} \propto T^4_{\text{wall}} - T^4_{\text{liquid}}$

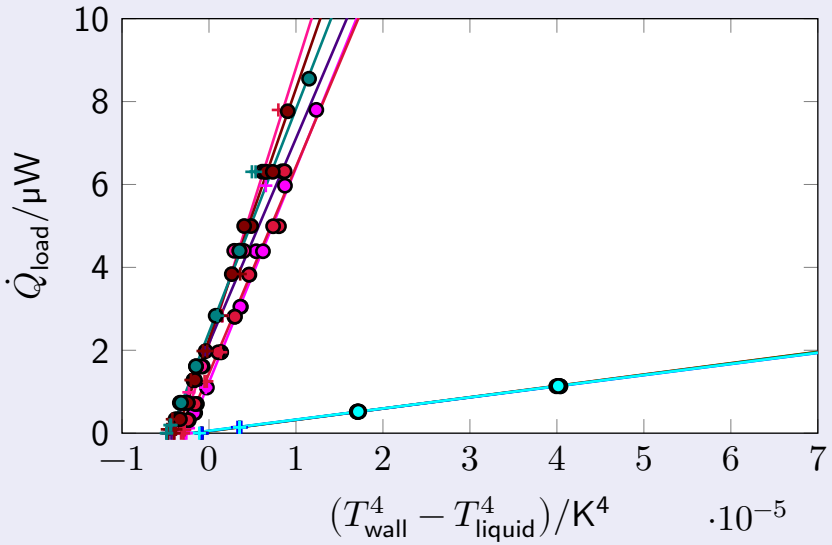
New dream setup silver sinter data





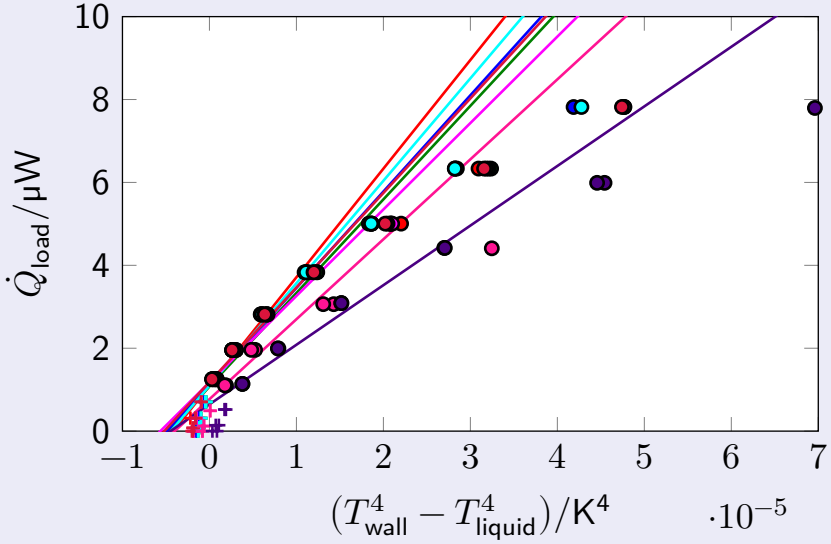
Comparing and fitting the heat transfer data

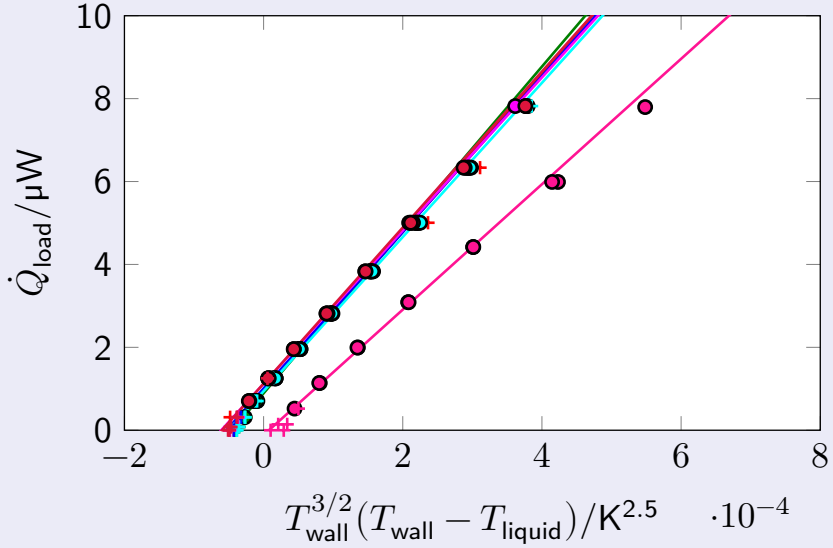
Old always setup Planck-like data



- old setup
  - ✔ $\dot{Q}_{\text{load}} \propto T^4_{\text{wall}} - T^4_{\text{liquid}}$
- new setup ($T_{\text{wall}} = T_{\text{SINTER}}$)
  - ✘ $\dot{Q}_{\text{load}} \propto T^4_{\text{wall}} - T^4_{\text{liquid}}$
  - ✔ $\dot{Q}_{\text{load}} \propto T^{3/2}_{\text{wall}}(T_{\text{wall}} - T_{\text{liquid}})$

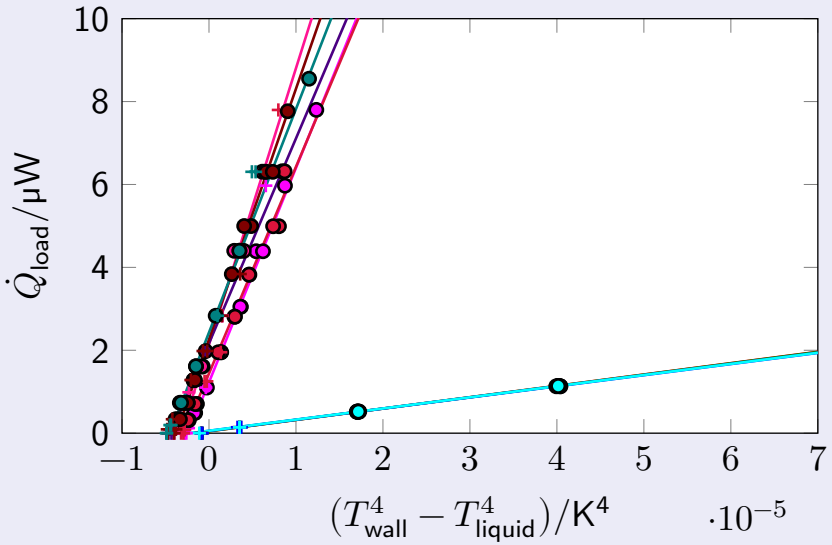
New dream setup silver sinter data





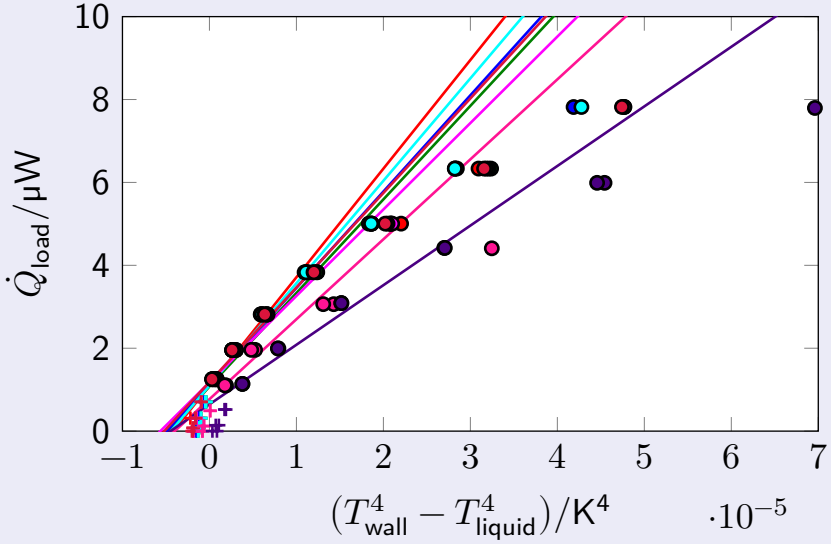
Comparing and fitting the heat transfer data

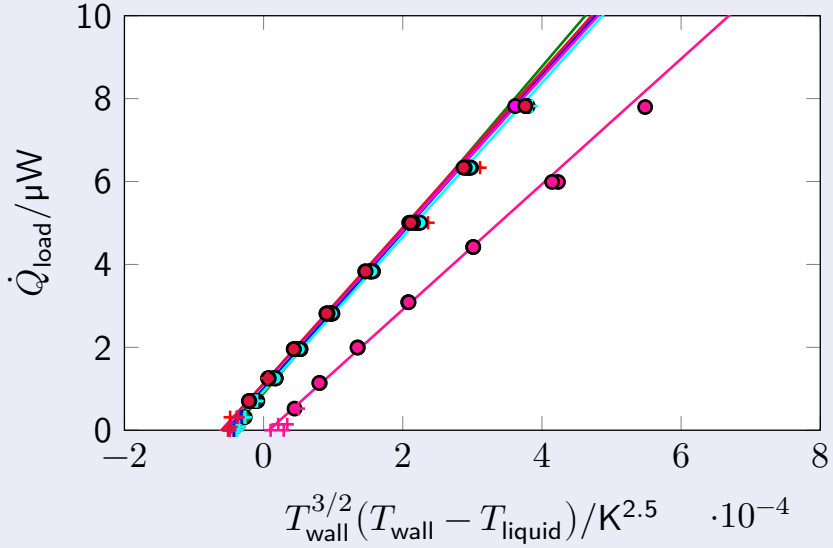
Old always setup Planck-like data



- old setup
  - ✔ $\dot{Q}_{\text{load}} \propto T^4_{\text{wall}} - T^4_{\text{liquid}}$
- new setup ($T_{\text{wall}} = T_{\text{SINTER}}$)
  - ✘ $\dot{Q}_{\text{load}} \propto T^4_{\text{wall}} - T^4_{\text{liquid}}$
  - ✔ $\dot{Q}_{\text{load}} \propto T^{3/2}_{\text{wall}}(T_{\text{wall}} - T_{\text{liquid}})$
- but, except for 1 fit
  - ☞ negative instead of zero offset

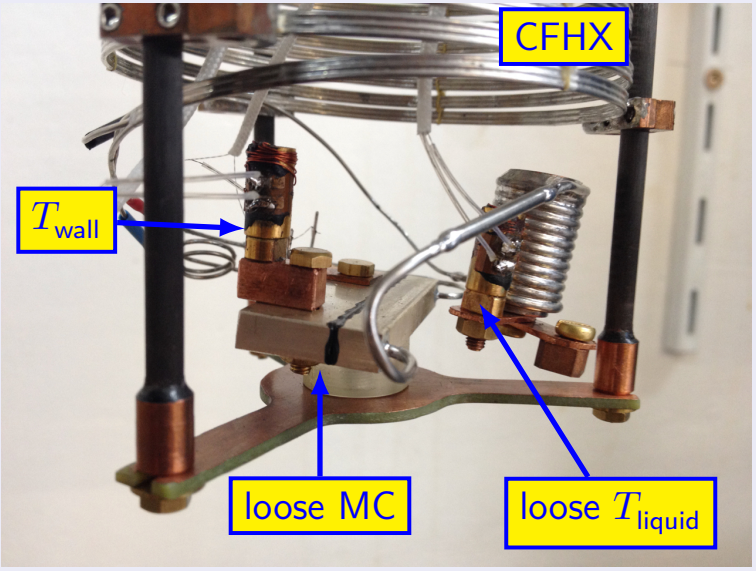
New dream setup silver sinter data

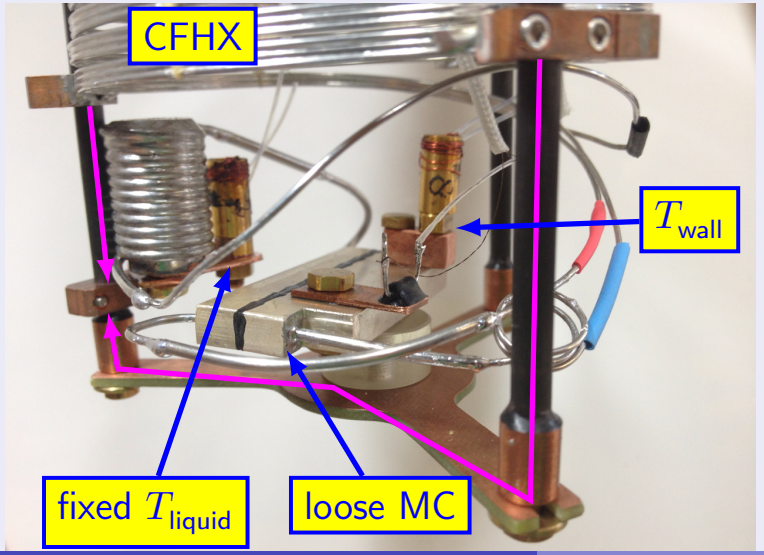




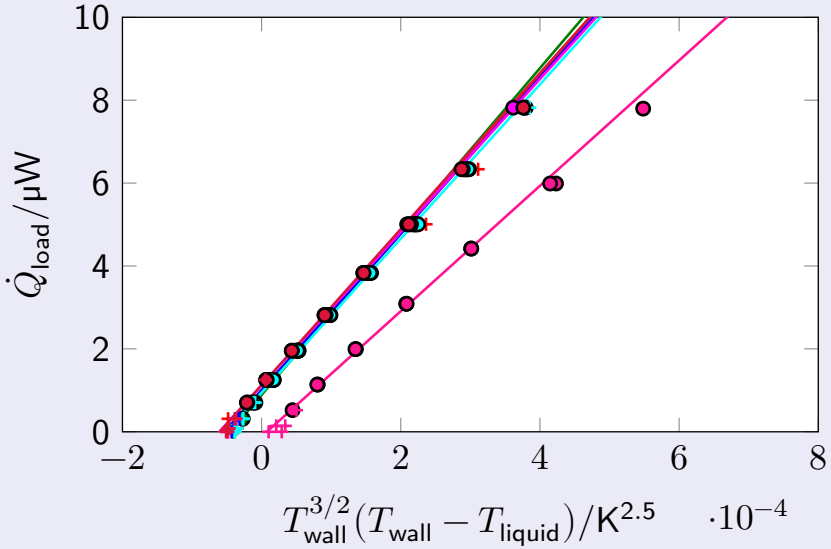
Comparing and fitting the heat transfer data

Heat leak through CFRP?





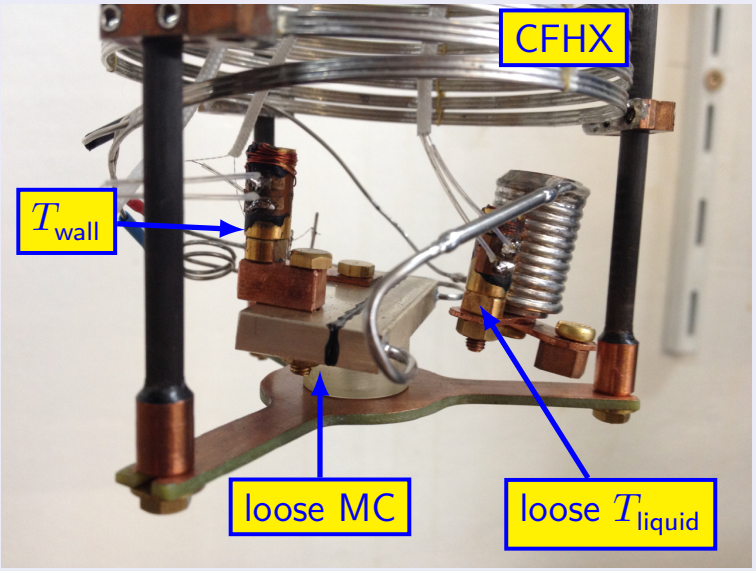
Discuss new dream setup fits



1. zero offset for "loose" T_{liquid}
2. negative offset for "fixed" T_{liquid}
   - Kapitza: $\sum \dot{Q}_{\text{CFRP}} \approx 60\,\text{nW}$
   - $T_{\text{CFRP}} \geq 0.25\,\text{K}$ at CFHX while $T_{\text{CFHX}} \leq 0.1\,\text{K}$
   - poor CFRP thermal anchoring due to clamping only?

Comparing and fitting the heat transfer data

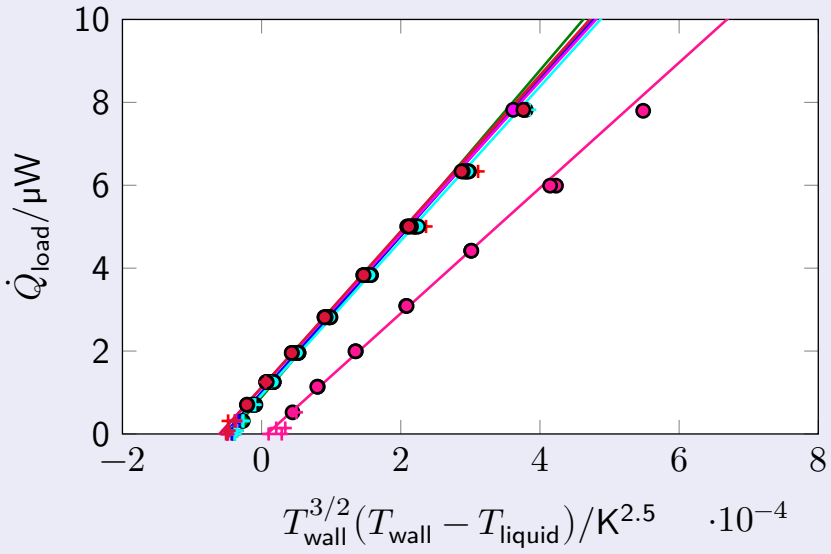
Heat leak through CFRP?



Remember

- $\dot{Q} = A\sqrt{\frac{k_M}{r_{KV}}}T_S^{3/2}(T_S - T_M)$
- $\Lambda = \sqrt{k_M r_{KV} T_S^{-3}}$
- 1 mm sinter thickness

Discuss new dream setup fits



1. only "loose" T_{liquid} data is valid
2. $k_M \approx 5 \times 10^{-4}\,\text{W m K}^{-1}$ (?)
   and $A = 40\,\text{mm}^2$ fit leads to
   $r_{KV} \approx 3.5 \times 10^{-9}\,\text{W m}^{-3}\,\text{K}^{-4}$
   $T_S = 0.10\,\text{K}$: $\Lambda \approx 42\,\mu\text{m}$
   $T_S = 0.05\,\text{K}$: $\Lambda \approx 120\,\mu\text{m}$

Outline

1. ^{3}He-^{4}He Dilution Refrigeration Crash Course
2. Experimental Setup
3. Thermodynamic Results
4. Thermal contact
5. Conclusion

Summary and conclusion

Cooling power of zero gravity compatible ^{3}He-^{4}He mixing processes

- old constant x process $\Longrightarrow$ $\frac{\dot{Q}_{\text{load}}}{\dot{n}_4 T_{\text{liquid}}^2} = (2.95 \pm 0.19)\,\text{J}\,\text{mol}^{-1}\,\text{K}^{-2}$
- new constant μ_4 process $\Longrightarrow$ $\frac{\dot{Q}_{\text{load}}}{\dot{n}_4 T_{\text{liquid}}^2} = (5.20 \pm 0.11)\,\text{J}\,\text{mol}^{-1}\,\text{K}^{-2}$
  - primary role of silver sinter as superleak
  - only way to meet X-IFU cryogenic requirements (CNES contract)

^{3}He-^{4}He thermal conductivity limited Kapitza heat transfer

- we find 2.5× more heat transfer than Cousins et al, PRL 73, 2583
  - secondary role of silver sinter to increase heat exchange surface
  - input for design optimization

CNES funding to assure procurement and optimize sinters for

- superleak properties
- thermal contact properties
- mechanical properties (rocket launch)